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The volume just completed contains 683 pages of scientific material, exclusive of Index and similar matter. The volume, which contained two special issues, one on reefs and one on feldspars, sold for $6.00—less than 1 cent a page. Despite rising printing costs and a return to the prewar volume of material, we have maintained the prewar subscription price. If the *Journal* continues to receive the support of its readers, it will remain a "best buy" in 1951.

Among the papers to appear in early issues of the *Journal* are:

"Glacial History of Wolf Creek, St. Elias Range, Canada." By ROBERT P. SHARP

"Geometry of Shearing Stress and Relation to Faulting." By ROBERT E. WALLACE

"On the Variations in the Relative Abundance of the Carbon Isotopes in Carbonate Minerals." By FRANS E. WICKMAN, R. BLIX, and H. VON UBISCH

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——— and DUNSANY, A. J. (1929*a*) Early Ordovician faunas of South Dakota: U.S. Geol. Survey Bull. 444, pp. 1–76.

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January 1951

INTERSECTING MINOR RIDGES AND PERIGLACIAL FEATURES IN THE LAKE AGASSIZ BASIN, NORTH DAKOTA[1]

LELAND HORBERG
University of Chicago

ABSTRACT

Low, intersecting ridges, 3–10 feet high and 75–500 feet wide, with intervening depressions form a fracture pattern which is strikingly revealed on airplane photos of the flat Lake Agassiz plain. The ridges occupy the axial part of the old lake basin and are known to extend from Fargo, North Dakota, northward to well beyond the Canadian boundary. Because the ridges are composed entirely of the underlying lake clays and surface soils, they cannot be explained by ordinary agents, such as wind, waves and currents, or glaciers.

It is proposed that the ridges represent frozen-ground structures formed during retreat of the late Wisconsin ice. This is supported by the occurrence of periglacial involutions, fossil ice wedges, and polygonal and network soil patterns in the lake sediments.

INTRODUCTION

Airplane photos of the central portion of the Lake Agassiz plain in northeastern North Dakota reveal a fracture system of low, intersecting ridges which is not evident from the ground. The fracture pattern, physiographic relations, and the uniform clay composition of the ridges indicate that they were not formed by common geomorphic agents known to have been active in the region. Structure soils having a fracture pattern do not appear to have been described previously, and to date it has not been possible to recognize them on photos of other areas. It is intended in the present paper to bring these unusual features to general attention, to describe them, and to suggest possible modes of origin.

The study is based on examination of air photos and on field observations made during four weeks in the spring of 1948. The field study involved a traverse of the central part of the lake basin between Fargo, North Dakota, and Winnipeg, Manitoba, and detailed examination of exposures and mapping in eastern Pembina and Walsh counties, North Dakota, where the ridges are most conspicuous (fig. 1).

Exposed sections of glacial deposits in the region are very limited and occur mainly along the Red River and as shallow cuts along roads and drainage ditches. The area studied is covered by U.S. Department of Agriculture photographs and by the Bathgate, Glasston, Drayton, and Pembina quadrangle maps.

REGIONAL RELATIONS

The Lake Agassiz plain and its shoreline features were formed as the Wisconsin Mankato glacial lobe retreated north-

[1] Manuscript received May 17, 1950.

ward along the Red River Basin and waters were impounded against the divide to the south (fig. 1) (Upham, 1896; Leverett, 1932, pp. 119–141). Drainage of the lake was southeastward through the Minnesota River Valley into the Mississippi headwaters at St. Paul. It is believed that, when the ice had retreated to the Lake Winnipeg region, the lake was partially drained through a different outlet, possibly to the east, and that a second expansion of the lake was brought about by a glacial readvance (Johnston, 1916; 1946, p. 3). All but the three highest beaches are thought to have been formed during the second stage. Intermittent isostatic adjustments occurred during and following ice retreat, so that the ancient shore lines are upwarped to the north along at least seven parallel hinge lines, which trend west-northwest. The total uplift recorded by the highest

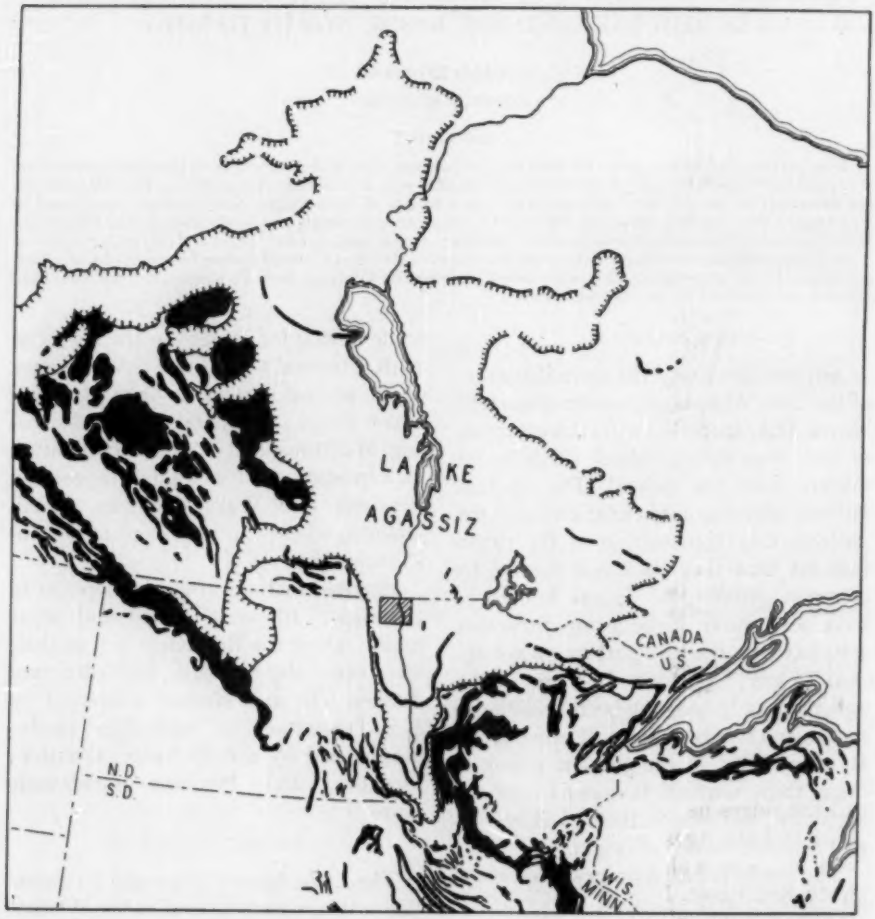


FIG. 1.—Map of Lake Agassiz and glacial moraines, showing area studied

Herman beach between the south end of the lake and the North Dakota–Manitoba boundary is about 200 feet (Johnston, 1946, pp. 12–17).

The ridged area occurs in the lowest and flattest part of the basin along the Red River as a strip 10–25 miles wide. It extends from the vicinity of Fargo northward to near Winnipeg, thus covering a minimum area of the order of 3,500 square miles.

In Pembina and Walsh counties nearly all the ridges lie below the lowest shore lines of Lake Agassiz (fig. 2), where the regional slope is about 2 feet per mile toward Red River. Most of the ridges are confined within a 10-foot contour interval on the lowest part of the lake floor, so that only about 15 feet of water in the original basin would have been needed to cover the entire ridged area. The topography of the area is monotonous lake plain, and, except for an isolated low ridge, the glacial features on the underlying drift sheet are completely buried by lake clays. This ridge, which is located 15 miles west of Pembina (fig. 2), is 8 miles long and ¼ mile wide, and its slightly sinuous outline and general east-west trend, normal to the end-moraines farther west, indicate that it is probably a partially buried esker. However, there are no exposures that reveal its composition.

Shore-line features are virtually absent in the ridged area, and the three

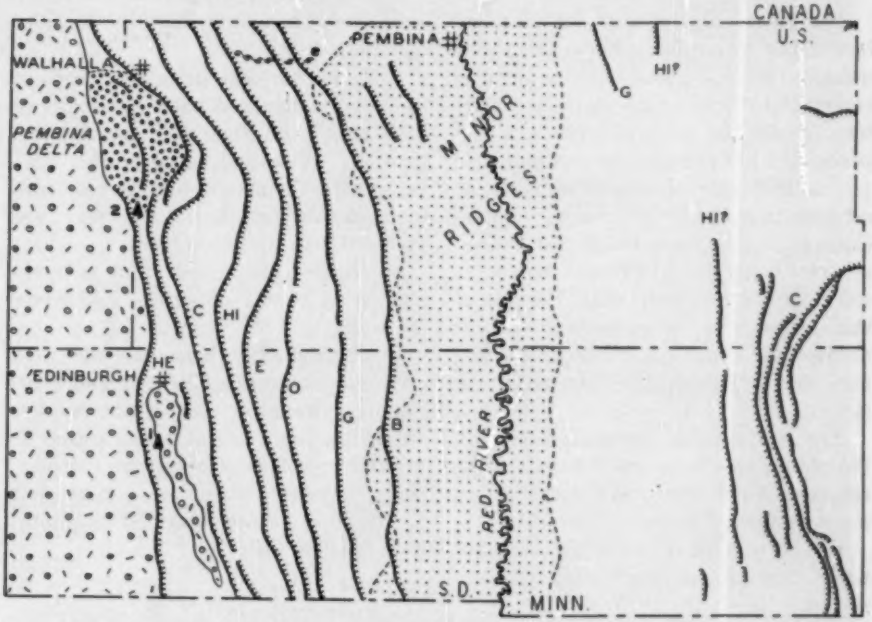


FIG. 2.—Ridged area and Lake Agassiz beaches in the Pembina area, N.D. Beaches in descending order are: *HE*, Herman; *C*, Campbell; *HI*, Hillsboro; *E*, Emerado; *O*, Ojata; *G*, Gladstone; *B*, Burnside; and the two lowest beaches, Ossowa and Stonewall. Horrigan Ridge esker at *e*. Locality *1*, involutions (fig. 6); locality *2*, gravel wedges (fig. 7).

beaches which extend into it are scarcely recognizable (Burnside, Ossowa, and Stonewall, fig. 2). The higher beaches to the west, however, are strongly developed.

DESCRIPTION OF RIDGES

GENERAL

The ridges and related features are best shown by airplane photos and photo mosaics (pls. 1, 2), and without them it is doubtful whether their distinctive pattern would be recognizable. On the photos the low ridges, 3–10 feet high and 75–100 feet wide, stand out as light-colored strips and the intervening depressions as angular dark-colored areas, the contrast being due to differences in soils, soil moisture, and vegetation. Because of the ridges, the area is both poorly drained and difficult to drain and is less desirable for agriculture than adjoining lands.

The outstanding features shown by the photos (pls. 1, 2) and the map of the ridges in eastern Pembina County (fig. 3) are summarized below.

1. The pattern of the ridges is essentially that of an intersecting fracture system

2. Major and minor ridges outline primary and subordinate areas within the pattern.

3. Certain major ridges, commonly with north-northwest trends, are broadly curved (fig. 3).

4. There is no evidence of superposition of ridges.

5. The ridges and interridge areas are about equal in width, the average being about 150 feet and the range 75–500 feet.

6. A few major ridges are continuous for distances up to 5 or 6 miles (fig. 3).

7. The transition from the ridged area to the adjoining lake plain is marked by marginal facies patterns of different types, which in places show inversion of positive and negative elements.

8. Isolated tributaries of the Red River apparently are uninfluenced by the ridgings (fig. 3).

9. Except in local areas, the trends of the minor ridges and Lake Agassiz shore lines intersect rather than parallel one another. At several places ridges continue without interruption across shore lines, indicating that the ridges are younger than the shore lines.

10. Ridges are absent from an early postglacial terrace along the Red River (pl. 1; fig. 3).

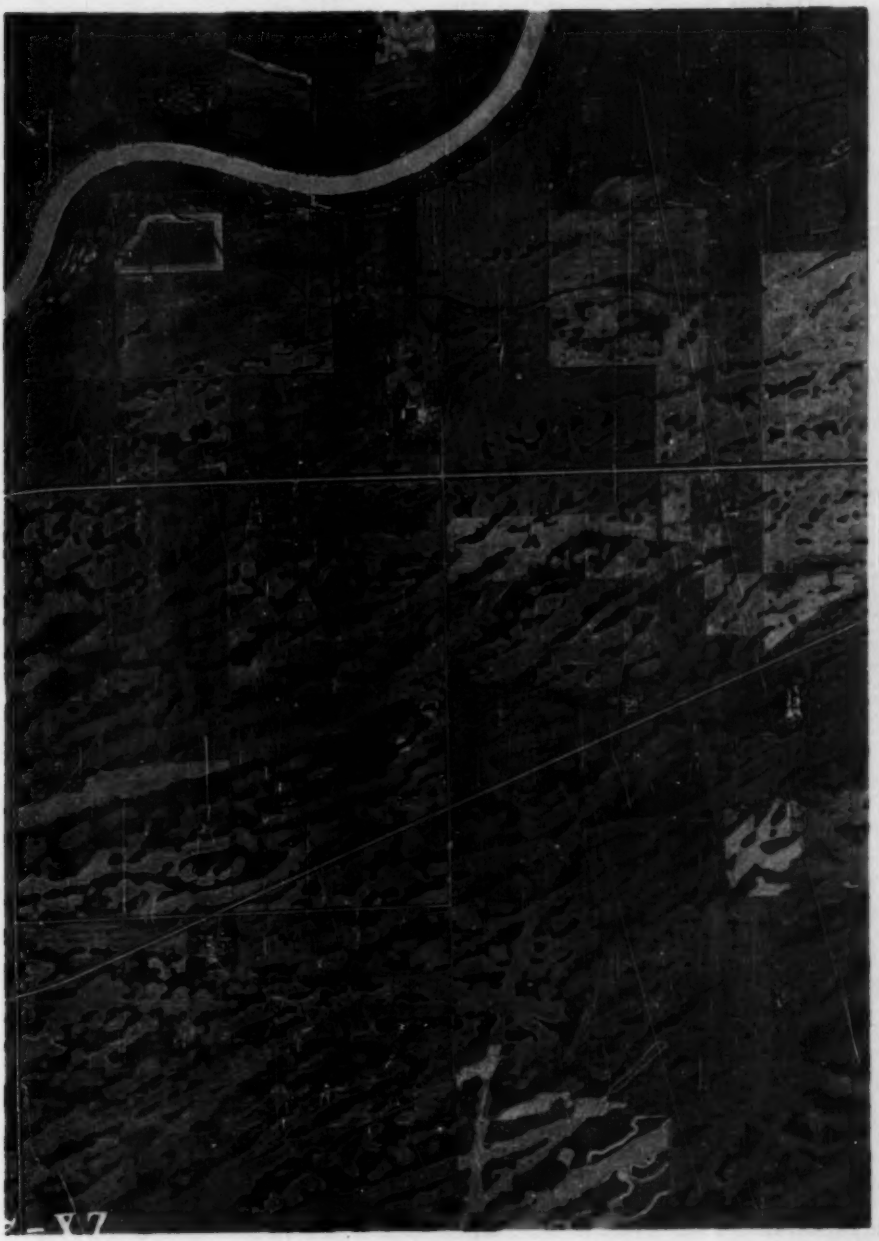
On topographic maps of the area (Bathgate, Drayton, Glasston, and Pembina quadrangles) the structures are shown by 5-foot contours and appear as a patchy system of ridges and depressions suggesting dune topography, but the fracture pattern revealed by photos is completely lost.

FRACTURE PATTERN

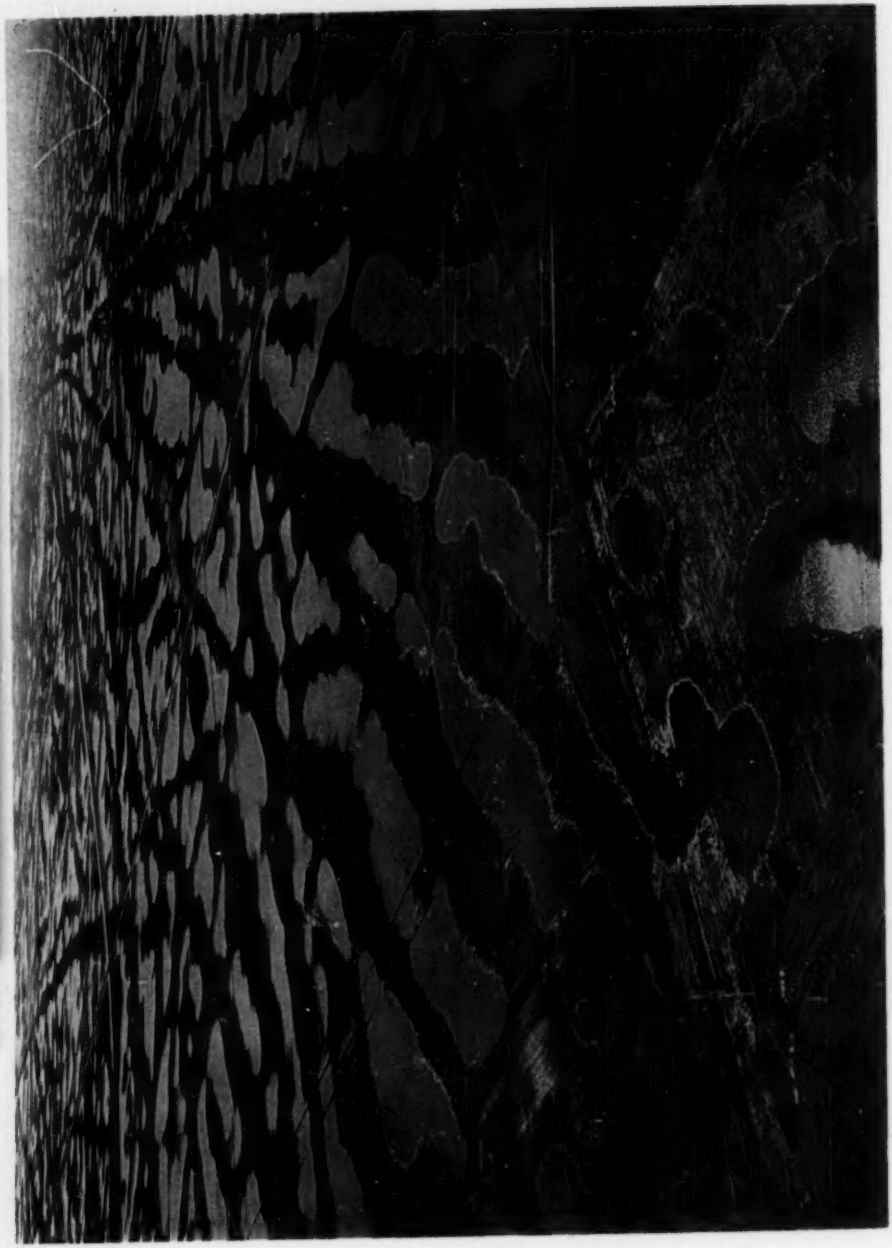
The trends of the ridges have remarkably consistent orientations in eastern Walsh and Pembina counties. This is not readily apparent from the photos but is revealed when the strikes of individual ridges are measured and plotted (fig. 4). Measurements were made directly from the photos along north-south and east-west traverses in ten local areas, ranging in size from less than a square mile to about two townships. An average of sev-

PLATE 1

Vertical aerial photograph of minor ridges near Pembina, North Dakota, with Red River and terraces (*T*) on right (secs. 27, 28, 29, 32, 33, and 34, T. 163 N., R. 51 W., Pembina County, North Dakota). Roads follow section lines. U.S. Department of Agriculture photograph, 1948.



Vertical air view of minor ridges



Oblique air view of minor ridges

enty trends was measured for each area, giving a total of about seven hundred. The diagrams clearly indicate a primary trend of about N. 30° W. and a secondary trend at right angles to it of N. 60° E., with an apparently normal distribution of ridges about these two trends. The shifts of dominant trends from one local area to another and from one county to the other are 5° or less. Most of the broadly curved ridges have a general trend of about N. 60° W. (fig. 3).

The pattern is essentially a fracture pattern which could be duplicated in many places by similar diagrams of joints and faults in hard rocks.

MARGINAL FACIES

Minor relief features marginal to the intersecting ridges are discontinuous and less sharply defined, but they include a variety of forms not present in the central area. Of special interest are inversions in form from areas in which ridges delineate the pattern to adjoining areas in which the pattern is outlined by furrows. Although there are numerous transitional forms and variants, it is possible to recognize the six central types listed below (fig. 5).

1. Polygonal ridges (secs. 29, 30, 31, and 32, T. 155 N., R. 51 W.; secs. 1, 2, 3, and 10, T. 158 N., R. 52 W., Walsh County, North Dakota).

2. Cellular networks (secs. 8, 17, 19, and 20, T. 155 N., R. 51 W.; secs. 11 and 15, T. 158 N., R. 52 W., Walsh County; secs. 17 and 20, T. 159 N., R. 52 W., Pembina County, North Dakota).

3. Cuneiform ridges (secs. 35 and 36, T. 156 N., R. 51 W.; secs. 9, 10, and 15, T. 156 N., R. 53 W., Walsh County).

4. Furrow polygons (secs. 3 and 4, T. 158 N., R. 53 W., Walsh County; secs. 2, 3, 10, 11, 21, 22, and 27, T. 159 N., R. 51 W., Pembina County).

5. Furrow networks (secs. 1 and 12, T. 158 N., R. 51 W., Walsh County; secs. 13 and 14, T. 159 N., R. 51 W., Pembina County).

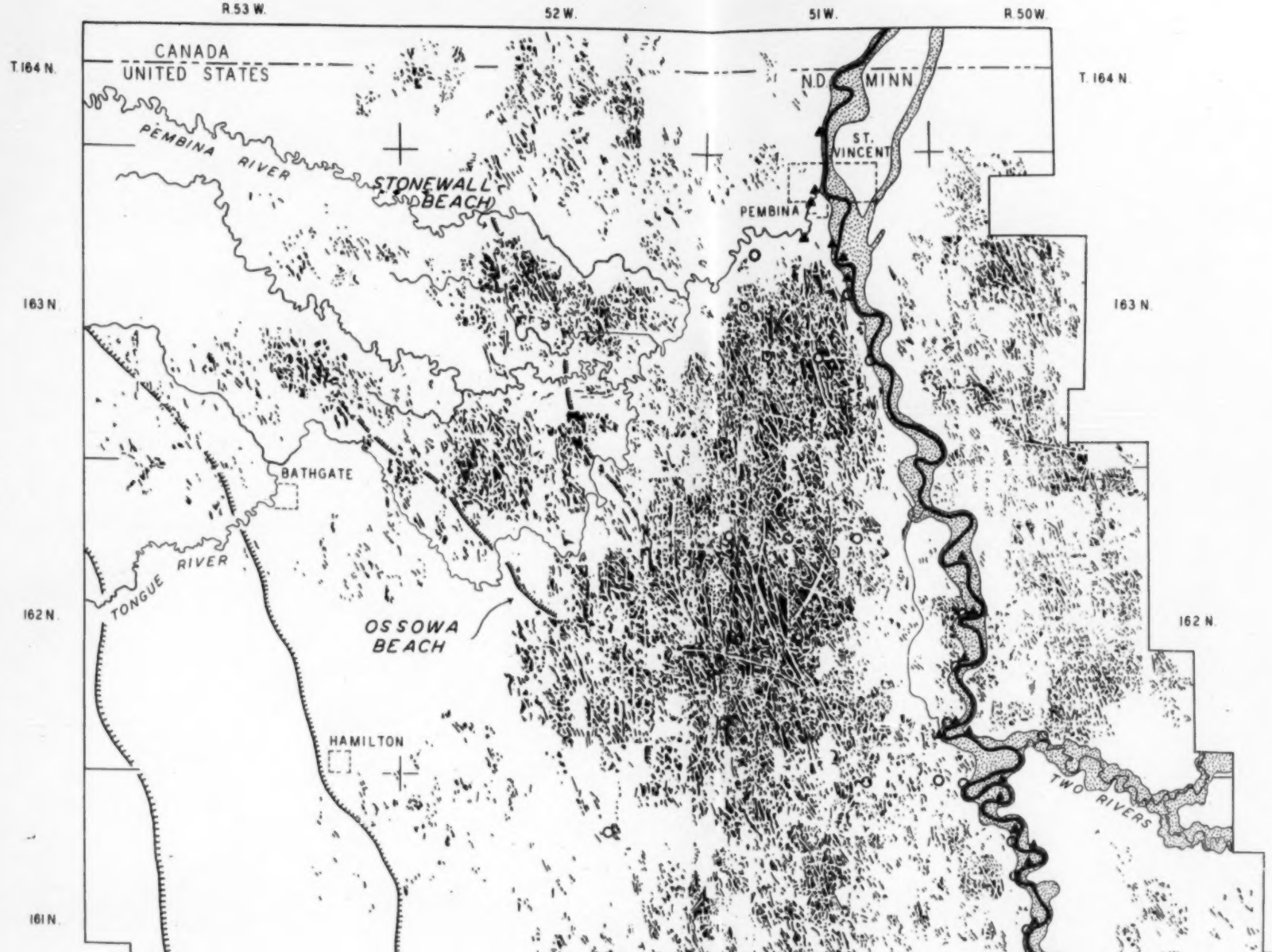
6. Cuneiform furrows (secs. 6 and 7, T. 160 N., R. 49 W.; secs. 13, 14, 23, and 24, T. 160 N., R. 50 W., Kittson County, Minnesota).

The polygonal and network patterns and the inversion of positive and negative forms are of particular interest because closely comparable features of similar scale are known in permafrost areas. The width of the areas between ridges or furrows varies from about 50 to over 300 feet, the average being about 150 feet. In present permafrost areas, widths are reported to range from about 25 to 325 feet (Cailleux, 1948, pp. 23–24) and to reach widths of 50 feet in northern Alaska (Leffingwell, 1919, p. 211); 135 feet in northern Canada (Nichols, 1932, p. 268); 150 feet in Baffin Land (Paterson, 1940, fig. 1, p. 100); 65 feet in Spitzbergen (G. Holmsen, cited by Leffingwell, 1919, p. 224); 120 feet (40 paces) in northern Siberia (A. T. von Middendorff, cited by Leffingwell, 1919, p. 215); and 65 feet in the Taimyr Peninsula, Siberia (Troll, 1944, p. 637).

The general term *Strukturboden* has been used to include large-scale surface markings of this type as well as smaller forms, such as stone polygons, stone nets,

PLATE 2

Oblique aerial photograph of minor ridges near Pembina, North Dakota, during flood stage of Red River in the spring of 1948. View is to the northwest of same general area as plate 1. Photograph by Gifford Herron, *Fargo Forum*, Fargo, North Dakota.


R.53 W.
52 W.
51 W.
R.50 W.
T.164 N.
CANADA
UNITED STATES
N.D.
MINN
PEMBINA RIVER
STONEWALL BEACH
ST. VINCENT
PEMBINA
163 N.
BATHGATE
TONGUE RIVER
162 N.
OSSOWA BEACH
HAMILTON
TWO RIVERS
161 N.

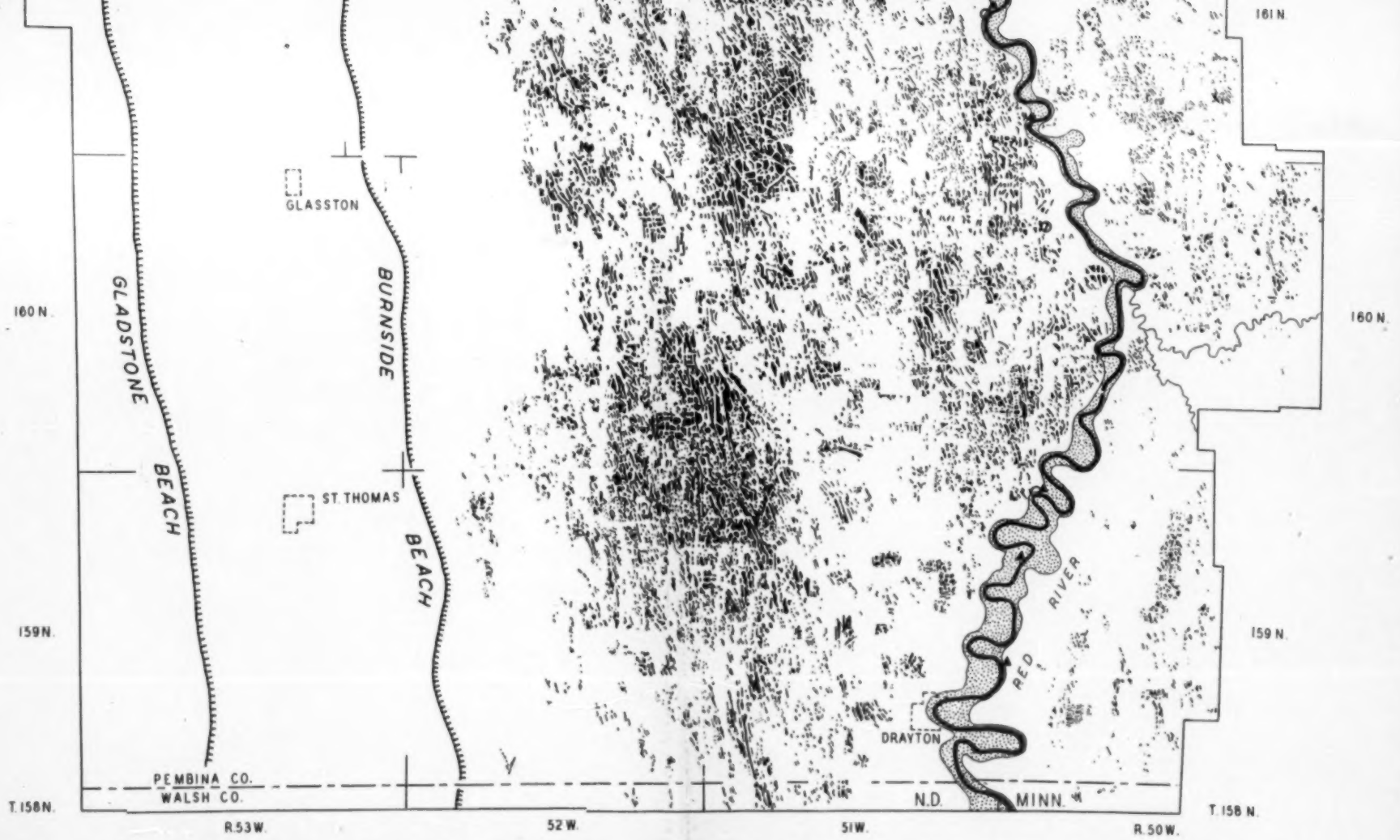


FIG. 3.—Minor ridges in eastern Pembina County, N.D. Based on U.S. Department of Agriculture airplane photo mosaics, 1948. Interridge depressions shown in black; terrace by stippled pattern; exposures of terrace deposits by triangles; and lake clays by circles.

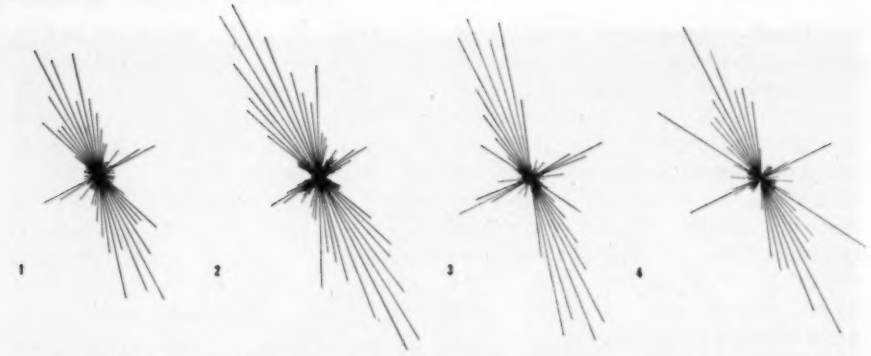


FIG. 4.—Rose diagrams of ridge trends. *1*, local area of 5 square miles, 3 miles south of Pembina, Pembina County, N.D. (pl. 1), 86 measurements; *2*, total of 524 measurements in eastern Pembina County, N.D.; *3*, total of 221 measurements in Walsh County, N.D.; *4*, local area of 10 square miles, 3 miles southeast of Grafton, Wash County, N.D., 67 measurements.

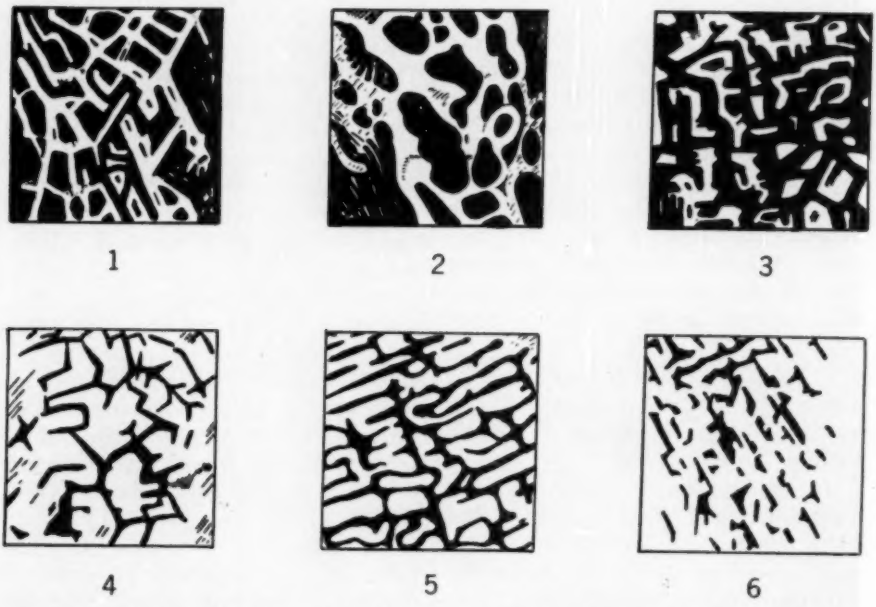


FIG. 5.—Marginal facies of structure soils. Each area is a quarter of a square mile. *1*, polygonal ridges, S. ½, S.W. ¼, sec. 3, N. ½, N.W. ¼, sec. 10, T. 158 N., R. 52 W., Walsh County, N.D.; *2*, cellular networks, N.E. ¼, sec. 19, T. 155 N., R. 51 W., Walsh County, N.D.; *3* cuneiform ridges, N.E. ¼, sec. 35, T. 156 N., R. 51 W., Walsh County, N.D.; *4*, furrow polygons, S. ½, S.E. ¼, sec. 22, N. ½, N.E. ¼, sec. 27, T. 159 N., R. 51 W., Pembina County, N.D.; *5*, furrow networks, W. ½, N.E. ¼, E. ½, N.W. ¼, sec. 24, T. 159 N., R. 51 W., Pembina County, N.D.; *6*, cuneiform furrows, W. ½, S.E. ¼, E. ½, S.W. ¼. sec. 6, T. 160 N., R. 49 W., Kittson County, Minn.

stone stripes, mud polygons, and related features (Washburn, 1947, p. 96). Various terms, including "tundra polygons," "Taimyr polygons," *Tetragonalboden*, and *Schachbrettboden*, have been applied to the larger forms found in polar areas (Troll, 1944, pp. 634–635).

COMPOSITION

Viewed from the ground, the structures appear as low swells and swales which could easily be overlooked (pl. 3, *A*). In cross sections both are seen to be composed of yellow lake clays and silty clays, with overlying soils which thicken in the depressions. In shallow exposures the clays are mechanically weathered and appear structureless, but in deeper cuts along the Red River they are distinctly laminated and jointed (pl. 3, *B*). The laminae consist of dark silty layers about 0.1 cm. thick and light clayey layers about 1.0 cm. thick and probably represent varves. Except for rare, isolated pebbles, coarser constituents are completely absent. The best-exposed sections through the ridges show that the clays have been crumpled and deformed, probably by both slumping and frost-action. The clays are leached to a depth of about 20 inches and are oxidized to depths of 15–30 feet.

At least 35 feet of clays are exposed along the Red River, and records of wells in the area (Simpson, 1929, pp. 182–187, 244–250; Allison, 1932, pp. 98–101) indicate thicknesses of from 60 to 130 feet. The total thickness of lake clays and underlying glacial drift above Paleozoic bedrock formations ranges from about 150 to 200 feet.

POSSIBLE RELATED FEATURES

The orientations of various features which may have a bearing on the origin of the ridges are listed in table 1. None of these shows a direct relation to the ridge trends, and indirect relations in most instances are only remotely possible or are discounted by other lines of evidence.

It is to be noted that the two lowest Lake Agassiz shore lines (Ossowa and Stonewall) occur at the western margin of the ridged area and numerous ridges continue without interruption across the shore lines (fig. 3). Elsewhere the shore lines would be intersected by the extended dominant trends of the major ridges.

TABLE 1

ORIENTATIONS OF FEATURES POSSIBLY RELATED TO THE MINOR RIDGES, PEMBINA AND WALSH COUNTIES, NORTH DAKOTA

Minor ridges, average.. (N. 60° E.)	N. 30° W.
Lake Agassiz beaches, average.....	N. 12° W.
Stonewall.....	N. 27° W.
Ossowa.....	N. 45° N.
Burnside.....	N. 11° W.
Gladstone.....	N. 10° W.
Isobase of Lake Agassiz beaches (Johnston, 1946, fig. 1).....	N. 55° W.
Contours of present land surface, average.....	N. 10° W.
Latest glacial movement, based on moraines.....	S.-W. 10° S.
Horrigan Ridge esker.....	E.-W.
Prevailing winds, all months of year (Bavendick, 1941, p. 1054).....	N.W.

It is only in local areas that the dominant ridge trends parallel the shore lines; over most of the area they diverge from both the shore lines and the surface contours. This is especially true east of the Red River, where surface contours indicate that the shore lines trend almost north-south and the ridges maintain a north-northwest direction.

RELATION TO TERRACES ALONG THE RED RIVER

The ridges are intersected by and do not appear on a younger terrace fill along the Red River. The terrace lies about 10 feet below the lake plain and 25 feet above river level and is continuous with

consistent relations along the Red River and the lower reaches of tributaries (fig. 3; pl. 1). It represents an old valley fill less than ½ mile wide, which is being trenched by the present stream. Essentially the same meanders that are now entrenched appear to have existed during the time of terrace development.

Most of the cuts along the river are in terrace deposits, and it is only where the river impinges against the lake plain that lake clays are exposed. The terrace deposits, as indicated by table 2, consist of clayey alluvium, rich in organic material, which was derived largely from the lake clays. Fossils, which occur throughout the deposit, include remains of gastropods, clams, bison, deer, and probably other vertebrates, as well as wood and peaty materials.

The terrace relations indicate (1) erosion of a valley somewhat wider than the present channel to a depth of at least 35 feet in the lake plain; (2) deposition of alluvium within the channel up to the level of the terrace; and (3) entrenchment to a depth of about 25 feet. On the basis of known regional history, this sequence of events may be explainable by changes in gradient resulting from isostatic uplift following glaciation. Rapid entrenchment immediately after drainage of the lake would have been followed by alluviation as isostatic uplift continued; and, as the rate of uplift diminished, normal headward erosion and adjustments of gradient may have caused cutting of the present channel. This interpretation and the physiographic position of the terrace indicate that it was formed in early postglacial time.

TABLE 2

SECTION OF TERRACE DEPOSIT ALONG RED RIVER 3 MILES NORTHEAST OF JOLIETTE, PEMBINA COUNTY, NORTH DAKOTA
(S.E. ¼, S.W. ¼, Sec. 13, T. 162 N., R. 51 W.)

Deposit	Thickness (Feet)	Depth (Feet)
Early postglacial terrace deposit:		
Clay, gray to black, rudely jointed, calcareous; fossil shells, vertebrates, and wood	11	11
Clay, gray to black, chalky aggregates, fossiliferous	8	18
Clay, with pockets of black organic material	1	19
Clay, interbedded yellow-gray and dark-gray layers, iron-stained, calcareous concretions, abundant fossils	8.5	27.5
Late Wisconsin Lake Agassiz clay:		
Clay, yellow, laminated, calcareous	4	31.5

RELATION TO SOILS AND LAKE SEDIMENTS

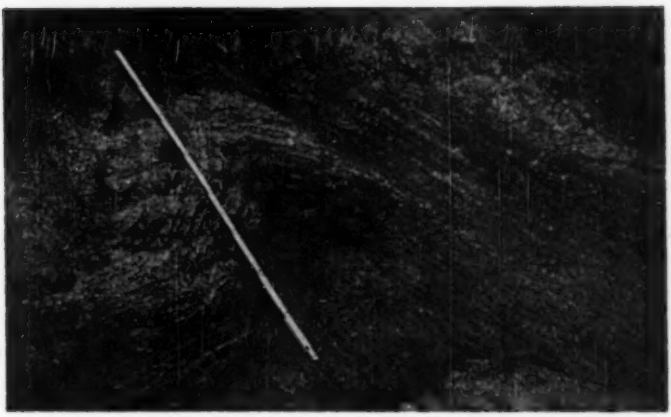
The minor ridges occur in areas of heavy chernozem soils and include clays and clay loams of the Fargo soil group (Nikiforoff, 1939, pp. 26–27, 69–95). Alkaline and immature phases are present

PLATE 3

A, Two ridges and intervening swale on Lake Agassiz plain, 3 miles south of Pembina, North Dakota.
B, Laminated Lake Agassiz clays exposed along Red River, 2 miles southeast of Joliette, North Dakota (N.W. cor., sec. 1, T. 161 N., R. 51 W., Pembina County, North Dakota).
C, Folded lake clays exposed along drainage ditch. Same locality as *B*.

A

B



C

Lake Agassiz clays

B

A

C

Involutions and wedge structures

where drainage is poore . A description of the generalized soil profile is given in table 3.

The ridges and soil types are related to changes in topographic position and to the lateral gradations within the lake deposits from clays in the center of the basin to silts and sandy silts in the marginal ridged area (Nikiforoff, 1939, p. 69). The alkaline and immature soils may have developed in large part as the result of poor drainage conditions induced by the ridging.

PERIGLACIAL FEATURES

GENERAL STATEMENT

A variety of geomorphic forms, surficial deposits, and structures in surficial deposits is believed to have formed in a zone of indefinite width marginal to the Pleistocene ice sheets (Smith, 1949). This periglacial environment was characterized by strong winds, low temperatures, permafrost, and intense frost-action. Aside from the eolian phenomena, its distinctive features are related to the presence of permafrost and intense frost-action, as evidenced by (1) products of accelerated mechanical weathering; (2) land forms and deposits due to solifluction and other mass movements; (3) fossil ground-ice wedges; (4) involutions and associated deformations in unconsolidated sediments; (5) certain types of natural mounds; and (6) polygonal ground, striped ground, and related features. Most of the features are being formed at present in high latitudes and at high altitudes. "Fossil" forms are found in both North America and Europe and are evidences of former more rigorous climatic conditions (see Smith, 1949, for summary and bibliography).

TABLE 3

GENERALIZED SOIL PROFILE IN EASTERN PEMBINA AND WALSH COUNTIES, NORTH DAKOTA

Horizon	Thickness (Inches)
A, black with organic matter, lumpy to blocky, noncalcareous	12–20
B, dark- to light-gray, compact; penetrated by vertical shrinkage cracks filled with black soil material from above, which are about 1 inch wide and extend from the surface to depths of about 3 feet; calcareous disseminated grains and nodules, some gypsum	12–18
C_1, yellow-gray to yellow weathered clays, oxidized, nonlaminated, calcareous	12–30
C_2, yellow clays as above, laminated	.....

In the Lake Agassiz region former permafrost conditions are indicated by deformed lake clays, involutions, fossil ice wedges, and polygonal ground.

DEFORMED CLAYS

Crumpled lake clays were observed within the ridged area at the bottom of deeper drainage ditches and in cuts along the Red River. One of the best exposures was found in a drainage ditch 2 miles southeast of Joliette, Pembina County, North Dakota (N.W. cor., sec. 1, T. 161 N., R. 51 W.), where folded lake clays occur 3–8 feet below the surface for a distance of about 25 feet (pl. 3, *C*). Asymmetrical folds with dips up to vertical could be traced without break from one side of the ditch across its bottom to the

PLATE 4

A, Involutions in Lake Agassiz deposits, 6 miles south of Edinburgh, North Dakota. Locality *1*, fig. 2. See fig. 6.

B, Gravel wedge in Lake Agassiz beach gravels near Concrete, North Dakota. Locality *2*, fig. 2. See fig. 7.

C, Soil wedges in weathered clays in highway cut, 3 miles northeast of Bowesmont, North Dakota.

other side. The largest fold has a height of at least 6 feet. Other deformed zones a few hundred feet away are separated by areas in which the clays appear to be horizontal.

At this locality it is difficult to explain the deformation other than by the former presence of masses of ground-ice. Structures of the magnitude and continuity indicated could not have been produced by slumping on the flat lake plain or along the sides of the ditch. At other localities, however, it is clear that comparable superficial structures are formed by slumping of thawed layers above frozen ground in the ditch banks. It is also possible that some of the steeply dipping clays exposed along the Red River were deformed by mass movements of larger scale.

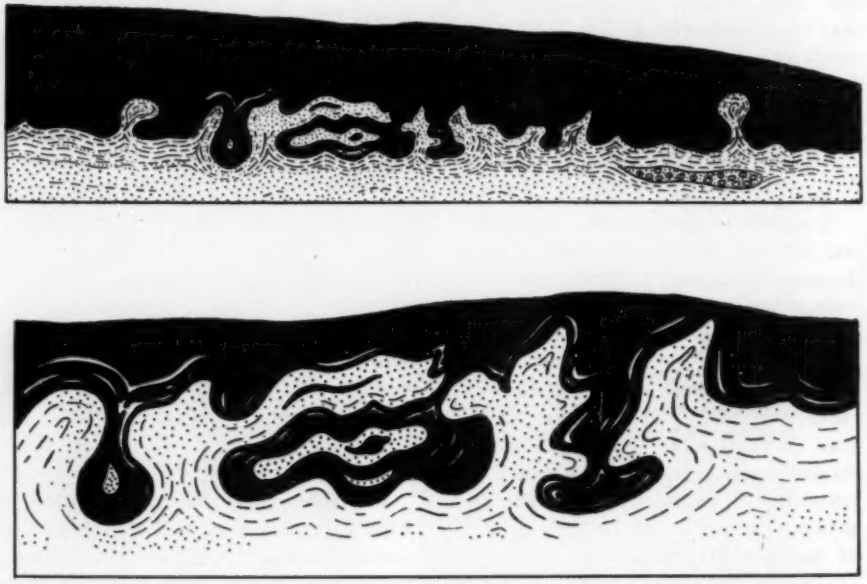


FIG. 6.—Involutions in Lake Agassiz deposits near Edinburgh, N.D. (fig. 2, locality 1; table 4). Upper sketch shows exposure 4×15 feet; lower, 2×6 feet. Clay shown in black.

INVOLUTIONS

An involuted zone in near-shore facies of the lake sediments west of the ridged area is exposed in a highway cut on the north side of South Branch Park River, 6 miles south of Edinburgh, North Dakota (figs. 2, 6; pl. 4, *A*). The section is situated at the western edge of the Leaf Hills moraine in shore deposits laid down along the eastern side of the Golden Valley embayment at the Herman stage of the lake. The units exposed are described in table 4.

The involutions occur at the transitional contact between surficial clays and underlying silt and sand at a depth of 12–18 feet below the original ground surface. They form a zone, 1½–2 feet thick, of completely kneaded, interpenetrating

masses of clay and silty sand. Intrusion appears to have been both upward and downward, but the most complex and sharply defined structures are masses of clay intruded downward into the sand. These masses have characteristic dumbbell- and boot-shaped forms (*Brodelboden*) and have no linear continuity normal to the face of the exposure. In places nests of sand form the centers of clay masses. Complex, flowage-type structures within the sand are outlined by silty and iron-stained layers.

The structures are identical in all essential respects with features described from a few localities elsewhere in North America (Denny, 1936; Sharp, 1942; Schafer, 1949, pp. 156–165) and from numerous localities in Europe (Steeger, 1944; Nørvang, 1946; see Sharp, 1942, and Smith, 1949, for earlier references). They are generally believed to be the result of plastic deformation produced by differential freezing and thawing and growth and melting of masses of ground-ice above perennially frozen ground. This interpretation appears to be the only one applicable to the structures described above, as there is no evidence that they could have been formed by ice-shove, differential loading, or mass movements.

Similar features were not found elsewhere in the area, but flowage structures in silt layers in gravel are associated with the gravel wedges described below.

WEDGE STRUCTURES

Gravel wedges.—Gravel casts of possible ground-ice wedges, which occur in Herman beach gravels on the south side of the Pembina delta, are exposed in a gully just south of the Tongue River on the west side of North Dakota Highway 32 about 1 mile southeast of Concrete, North Dakota (figs. 2, 7; pl. 4, *B*). The wedges occur at the top of the upper gravel in the section described in table 5.

TABLE 4

LAKE AGASSIZ DEPOSITS 6 MILES SOUTH OF EDINBURGH
WALSH COUNTY, NORTH DAKOTA
(S.W. Cor., Sec. 15, T. 157 N., R. 56 W.)

Deposit	Thickness (Feet)	Depth (Feet)
Soil, black to gray	1.5	1.5
Clay, silty, gray, upper 12 feet poorly exposed	15.0	16.5
Clay, dark-gray, involuted	1.0	17.5
Clay, light-gray to white, poorly stratified	2.5	20.0
Involuted layer involving clay, silt, and sand	1.5	21.5
Sand, silty at top, interbedded silt sand and gravel, foresets, cut-and-fill structures	6.0	27.5

The disturbed zone extends to a depth of 7 feet below the surface and is shown by wedge structures, squeezed and contorted beds of silt and sand, and confused orientations of shale pebbles, which originally lay with their flat surfaces horizontal.

The wedges are tack-shaped or branching forms which are 2–5 feet in length and flare at the top to a maximum diameter of about 2 feet. They intersect the face of the cut at various angles and have

a horizontal extent of at least 6 feet. The fill is of finer texture than the enclosing gravel and consists of weathered shale gravel and pebbly loam in which the shale pebbles are oriented parallel to the margin of the structures. Pebbles bordering the wedges in the enclosing gravel also tend to have similar orientations but are less regular. The terminal portions of the wedges thin to narrow dikes and seams, which have the appearance of joint fillings. At the top they merge into the gray subsoil.

The deformed silt and sand layers in the enclosing gravel are cut by the wedges and appear to have been disturbed slightly earlier. The most conspicuous deformed layer is a poorly bedded yellow clayey silt which originally was a continuous, horizontal layer but

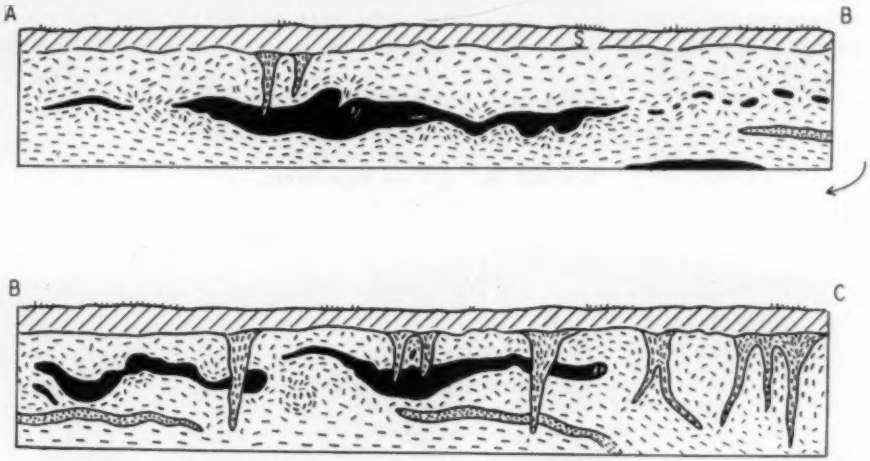


FIG. 7.—Gravel wedges in Lake Agassiz beach gravels near Concrete, N.D. (fig 2, locality *2;* table 5). Exposure is 7 feet high and 45 feet long. Silty clay shown in black; shale pebbles as dashes; and present soil zone (*S*) as diagonal lines.

TABLE 5

LAKE AGASSIZ DEPOSITS 1 MILE SOUTHEAST OF CONCRETE
PEMBINA COUNTY, NORTH DAKOTA
(N.E. ¼, S.E. ¼, Sec. 30, T. 161 N., R. 56 W.)

Deposit	Thickness (Feet)	Depth (Feet)
Soil, dark-gray to black	2	2
Gravel, largely flat pebbles of Cretaceous shale with average maximum diameter of about 2 inches, sandy matrix, silt and sand layers, upper 5 feet disturbed and containing wedge structures	12	14
Silt, brown, slightly sandy, poorly bedded, unconformity at base	4	18
Sand and gravel, interbedded silt layers, cross-bedded, irregular cut and fill	6	24
Sand, dark-brown to black carbonaceous stain, coarse, gravelly, unconformity at base	3	27
Cretaceous shale, dark-gray, platey, about 30 feet exposed	.....	.....

now is discontinuous, squeezed, and contorted (fig. 7). It thins from a thickness of about 2 feet to detached smears of silt. In places pebbles from the enclosing gravel are mixed with the silt. Variations in the level of the silt layer indicate a vertical displacement of several feet. The shale pebbles have conformable orientations near the margins of the silt and sand masses, but at intermediate points they are contorted into confused, nestlike structures. In places near the base of the exposure the pebbles assume their original attitude, with flat surface horizontal.

The wedges are smaller than some of the ground-ice wedges previously described, which reach widths of 8 feet and extend to depths of 30 feet below the surface. In other respects, however, they are comparable to similar structures described in North America (Horberg, 1949; Schafer, 1949, pp. 165–171), Europe (see Smith, 1949, for summary and references), and arctic regions (Leffingwell, 1915; 1919, pp. 179–242; Taber, 1943, pp. 1510–1519; Woods *et al.*, 1948, p. 498).

Other possible interpretations of the openings appear improbable: (1) desiccation cracks would not be so large or have flaring walls, nor would they develop in permeable gravels; (2) recent frost cracks of the appreciable size required do not appear to be known except in polar areas; (3) cracks produced by mass movements are excluded by the flat local topography and the divergent trend of the wedges; and (4) cavities formed by the decay of the roots of trees or large shrubs (Lutz and Griswold, 1939) would not have the horizontal continuity of the wedges, and there is no evidence that the natural vegetation of the area was anything other than grasses.

It is recognized that the permeability of the gravels presents difficulties to both the desiccation and the ice-wedge interpretations, but it is more likely that ice wedges could have formed from the surface in solidly frozen gravel than as shrinkage cracks in unconsolidated gravel.

Soil wedges.—Wedges of black soil material extending downward from the base of the topsoil into the underlying lake clays are characteristic features of the weathered zone over a large part of the central lake plain (pl. 4, *C*). They appear in almost every good exposure and were observed from the Fargo, North Dakota, area northward almost to Winnipeg, Manitoba. In the Pembina region they were well exposed in highway cuts 3 miles northeast of Bowesmont (E. line, S.E. ¼, sec. 31, T. 161 N., R. 50 W.), 3 miles south of Pembina (S. line, sec. 21, T. 163 N., R. 51 W.), and 1.4 miles south of Mountain (E. line, N.E. ¼, sec. 21, T. 160 N., R. 56 W.) in Pembina County.

Most of the wedges in the Pembina region are about 1 foot wide at the top and extend to a depth of about 3 feet. The wedges appear to increase in size to the north, and the largest ones, observed near Winnipeg, Manitoba, have a width of 3 feet at the top and extend to a depth of at least 8 feet. They have a horizontal extent of at least 10 feet in places, and their trends diverge to form an intersecting pattern. Some wedges branch downward, and a few are interconnected by veinlets of organic material. Except for segregations of yellow, oxidized clay in the centers of a few wedges, the fillings appear structureless and are indistinguishable from soil material in the overlying A zone. The enclosing weathered clays also are structureless, so the extent of deformation in the adjoining beds is unknown. At least three generations of structures are indicated in places:

(1) gray, bleached wedges intersected by structures 2; (2) black, prominent wedges described above; and (3) smaller vertical fracture fillings, related to the present soil profile, in which A-zone material penetrates downward into the B zone (Nikiforoff, 1939, p. 27).

It is uncertain that the soil wedges are related to the gravel wedges and should be considered periglacial features. Their size and outlines are comparable to many ice wedges, but the fills of organic soil material suggest a more recent age, unless a heavy vegetative covering is assumed for the periglacial area. The alternative that they represent filled desiccation cracks is supported by their occurrence in clays and clayey silts. Desiccation cracks up to 6 inches in diameter and over 10 feet in depth are reported by local residents as forming in the lake clays during the fall of unusually dry years. Typical shrinkage cracks, however, are rarely more than 1–2 inches across (Shrock, 1948, p. 195) and tend to have subparallel instead of flaring walls. It is clear that the wedges are older and differ in character from the smaller, desiccation fractures in the B zone of the present soil. Their interpretation as root casts is discounted by their horizontal continuity and intersecting pattern.

INTERPRETATION

The involutions, gravel wedges, and polygonal and network ground patterns described above record the former existence of permafrost in the area, although the interpretation of some of the deformed clays and soil wedges is uncertain. The periglacial features and the minor ridges formed during the same interval, following the draining of the lake and preceding the development of the present soils, and the polygonal and network ground are an intimate part of the general ridge system. It is mainly for these reasons that the intersecting ridges are considered permafrost features developed during retreat of the last Pleistocene ice sheet.

ORIGIN OF THE MINOR RIDGES

GENERAL STATEMENT

The origin of the ridges presents a problem to which multiple hypotheses should be applied, and, although a single interpretation will be urged, it is recognized that numerous uncertainties exist in the general explanation and especially in details of the processes involved. It is clear from previous descriptions that any hypothesis of origin must take into account the essential features which are evaluated below.

1. The uniform clay composition and fracture pattern indicate that ordinary geologic agents, such as glacial action, shore processes, and dune-forming winds, cannot be appealed to directly.

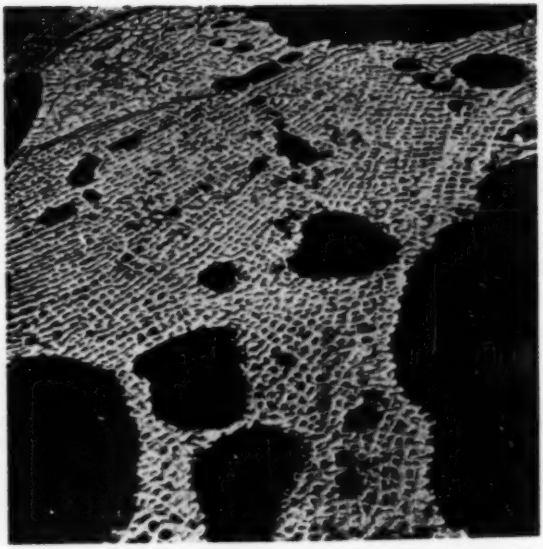
2. The consistent orientation of the ridges over an extensive area points to endogenous, rather than exogenous, causes.

3. The early postglacial age of the ridges indicates that they were formed by processes which are inactive or subordinate at the present time.

4. The presence of polygonal and network patterns in marginal facies of the ridge system and the occurrence of frozen-ground structures in the lake sediments strongly suggest that the ridges were formed in a permafrost environment.

Two interpretations based on processes that may have been active in the periglacial area will be considered: (1) fracture fillings deposited between blocks of lake ice at the closing stage of Lake Agassiz history and (2) tundra ridges due to ground-ice wedges.

A



B

Sea ice and tundra polygons

FRACTURE FILLINGS IN LAKE ICE

The closest approximation to the pattern of intersecting ridges shown by airplane photos of polar areas appears to be the pattern of open fractures and frozen leads which form at an early stage in the breaking-up of sea ice (pl. 5, *A*). As in the case of the ridge pattern, major and subordinate elements are present. The open fractures result mainly from movement by the wind after initial melting near shore, but narrow fractures also are caused by contraction at low temperatures or sagging where ice is afloat adjacent to fast ice.

Major difficulties in applying this pattern to the ridges arise from two important features of the ridges: (1) the subequal width of ridges and intervening depressions and (2) the consistent orientation of the linear elements. These features make it necessary to assume that the fractures in the ice were greatly enlarged *in situ* and that the intervening ice blocks remained in the same position until they melted. In order to explain the preservation of the ridges from wave attack and their apparent contemporaneous development, it is required also that the ridges be formed during the last freezing-over of the lake prior to drainage. The fact that a depth of only 10–15 feet of water would have been needed to cover most of the ridged area indicates that the lake during its final stages could have been frozen solidly to the bottom and that paleocrystic (perennial) ice may have remained from year to year, as reported in protected portions of polar seas at the present time (Kindle, 1924, p. 264). Under such conditions fractures in the ice may have been enlarged by lake water and ridges produced by movements of the ice blocks or deposition along the enlarged fractures. In addition to these difficulties, the hypothesis breaks down by its failure to explain the fact that at several places the ridges continue without interruption across shore lines and therefore are younger than the shore lines.

TUNDRA RIDGES

Tundra relief forms (pl. 5, *B*) are not known to have the distinctive fracture pattern of the typical North Dakota ridges. They have, however, the following features in common with the polygonal and network structures of the marginal facies: (1) comparable horizontal and vertical dimensions; (2) inversion of relief; and (3) occurrence in flat, poorly drained areas, commonly underlain by silts and clays.

The tundra structures generally are attributed to the growth of ice wedges which, together with ice layers and lenses, constitute the main occurrences of segregated ground-ice in perennially frozen ground. Most writers follow Leffingwell (1919, pp. 205–212, 223–224) in ascribing the wedges to filling of frost cracks and successive growth by addition of ice as they are reopened from year to year. More recently Taber (1943, pp. 1519–1527) concluded that they are formed as segregations of ground water in polygonal stockworks during downward freezing.

The wedges are expressed topographi-

PLATE 5

A, Sea ice with pools of water from melted snow in Barents Sea. 78°35′ N., 50°0′ E. Graf Zeppelin photograph by Basse (in Eckener *et al.*, 1933, pl. 33, fig. 2).

B, Tundra polygons in the Taimyr Peninsula, Siberia. 74°30′ N., 100°25′ E. (*ibid.*, pl. 8, fig. 32).

cally as furrows formed by the melting of the ice, as ridges produced by deformation of deposits adjoining the wedges, or in places as ridges with central furrows along their crests (Goussev, 1938, p. 377). In the Lake Agassiz area the critical evidence of single large wedge structures in the center of ridges or furrows along ridge crests was not observed. Whether this was because of their absence or because of the lack of suitable exposures is uncertain.

Except for the remarkable fracture pattern, there would be little hesitancy in interpreting the ridges as tundra forms. The fracture system thus suggests that more than one process may have been operative and that pre-existing structures on the lake floor may have determined the pattern of the ice wedges. A possible analogy is that of mud-crack patterns, which in places seem to be predetermined by original irregularities and structures in the bottom sediments (Shrock, 1948, pp. 189–195). Also, it is known from experimental studies with silts and clays that the form and size of ice segregations are determined by such pre-existing structures as laminae in varves, as well as by grain size and other factors (Beskow, 1935, pp. 28–30, 222–223; Taber, 1943, pp. 1522–1524). On this basis it is suggested that the distinctive pattern of the ridges may be inherited from a joint system in the clays developed during isostatic adjustment to glacial unloading; from irregularities on the lake floor determined by lake-ice fractures, as discussed above; or from unrecognized sedimentary structures within the lake sediments.

Isostatic upwarping of the area is shown by the deformed lake beaches, but there is no evidence of minor tectonic adjustments that could have accompanied it. It can be assumed, however, that they occurred along regional fractures in the underlying bedrock and were extended into the overlying glacial drift and lake clays at a time when they were completely frozen. This is uncertain at best, and both the nature of the fracture system in the underlying bedrock and the former depth of permafrost are unknown. In addition, it is unlikely that permafrost reached the required depth of 150–200 feet because of the relatively low latitude and the probable delay of its growth in the lake basin until after the lake had drained.

The ridge pattern can be explained most directly by inheritance from irregularities due to fractures in the lake ice. In this case fracture systems from more than one freeze-over of the lake could have been superposed to form the complex intersections, but the consistent trends of the ridges and their continuity across shore lines remain major objections. Greater objections are encountered, however, in other possible explanations. A regional fracture pattern could hardly be produced by depositional or erosional agents once active on the lake floor or by differential compaction of the lake sediments.

It is concluded that, although there is little basis for a satisfactory explanation of the fracture pattern, the ridge complex on the whole is best interpreted as a system of fossil tundra ridges of unusual type.

CONCLUSIONS

1. After the draining of Lake Agassiz in the closing stages of Wisconsin time and prior to entrenchment and deposition of a terrace fill along the Red River, a system of low, intersecting clay ridges was formed on the lake plain.

2. During a part of this interval a periglacial environment persisted long

enough for perennially frozen ground to develop in the lake sediments, as evidenced by deformed lake clays, involutions, wedge structures, and polygonal ground.

3. It is believed that the clay ridges represent an unusual type of tundra "polygon" (*Strukturboden*) produced by ridging along a system of ice wedges in the frozen ground.

4. The fracture pattern of the ridges may have been inherited from pre-existing structures produced in the lake clays by tectonic movements or the breaking-up of grounded lake ice.

5. The entrenchment of the Red River and the deposition of a terrace fill in early postglacial time could have been due to gradient changes produced by isostatic adjustment following glacial unloading.

6. Post-Wisconsin erosion in the ridged area has been minor except for local stream entrenchment and slope wash. Most of the lake plain is essentially an initial land surface, and the intersecting ridges remain as obstacles to drainage and land use.

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SOME ASPECTS OF THE SYSTEM H_2O-Na_2O-SiO_2-Al_2O_3[1]

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ABSTRACT

A small section of the system H_2O-Na_2O-SiO_2-Al_2O_3 was investigated at 300° and 450° C. Two new hydrated sodium aluminum silicate phases were found and their properties investigated. One of these phases appears optically isotropic and can be told from analcite with difficulty. The existence of solutions containing silica and alumina at these temperatures is demonstrated, and their importance to the granite problem is discussed.

INTRODUCTION

The quaternary system H_2O-Na_2O-SiO_2-Al_2O_3 is of importance for the understanding of the genesis of granites, soda pegmatites, and other soda-rich rocks. The stability relations in this system are of importance whether one considers diffusion, moving solutions, or melts responsible for the formation of this group of rocks.

Whether or not solutions or melts which contain considerable quantities of silica and alumina and from which, under the proper conditions, albite and quartz can crystallize can exist at relatively low temperatures, e.g., 300°–500° C., has been debated for years. Until recently the only data available on such systems have been the work of Goranson (1931). His results, though excellent, are restricted to granite + water, where the only independent variables were temperature and water content. In terms of the basic five-component system, H_2O-Na_2O-K_2O-Al_2O_3-SiO_2, in which simple granites are contained, this work of Goranson is extremely restricted.

On the basis of Goranson's experiments the existence of fluids at temperatures below 500° and containing sizable quantities of material capable of crystallizing rock-making minerals has been questioned. The existence of such solutions or melts and their properties are therefore of importance to students of petrology.

During the course of this work two new hydrated sodium aluminum silicates have been found. One of these appears optically isotropic and has an index close to that of analcite. It is possible that some of the analcite occurring in igneous rocks is in reality this "new" phase rather than analcite. The question of the primary nature of analcite is again considered.

In order completely to investigate the relationships in the four-component system H_2O-Na_2O-SiO_2-Al_2O_3, it is necessary to be able to vary independently the temperature, the pressure, and the proportion of each of the four components. The following work is preliminary with respect to the whole system for the following reasons: (1) Only two isotherms (300° and 450° C.) were investigated. (2) The pressure at 300° C. was equal to the vapor pressure of the solutions investigated. At 450° C. the pressure was variable and somewhat difficult to estimate. With the exception of the analcite-albite equilibrium, the pressures were all below 7,000 p.s.i. at 450° and below 2,000 p.s.i. at 300° C. (3) A fairly small region of the four-component tetrahedron was investigated—the low Al_2O_3 end, the only por-

[1] Manuscript received June 8, 1950.

tion amenable to liquidus investigation at these temperatures.

In order to determine the influence of Al_2O_3 upon equilibria in the ternary system, quartz solubility runs were made, as was done in the previous investigation (Friedman, 1950), the only difference being that varying amounts of Al_2O_3 were added. In all these runs quartz and albite plus two liquids and a gas were in equilibrium. If it is assumed that all the Al_2O_3 was converted into albite, thereby removing from solution almost all the Al_2O_3 and some Na_2O and SiO_2 and if one calculates the composition of the remaining solutions (and gas), it is found that their composition falls on the quartz saturation boundary AC (figs. 1, 2; table 1). In other words, it is assumed that Al_2O_3 enters the liquid and gas phases in only minor amounts. That it does enter the liquid phase is shown by the fact that the glass C (fig. 1), which, before the addition of Al_2O_3, is water-soluble, is, upon the addition of Al_2O_3 to the system, stabilized and rendered "insoluble." The glass is insoluble in cold water, only minor amounts of Na_2O and SiO_2 being leached out. If hot running water is used to dissolve it, the leaching is carried out until either a stiff gelatinous material is left as a residue or, in a few cases, a hard, porous, spongy mass remains. No analyses of the glasses have been attempted, since

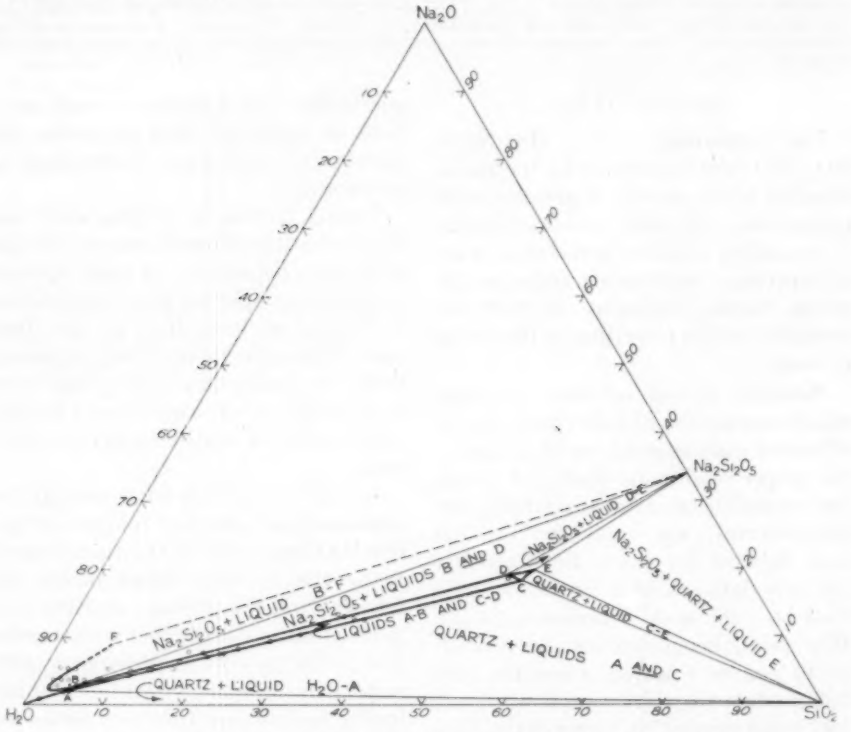

FIG. 1.—Polybaric saturation relations in the system H_2O-Na_2O-SiO_2 at 300° C.

it has been difficult to free the glass from albite or other aluminum-containing solid phases.

EXPERIMENTAL PROCEDURE

The runs in the quaternary system were made by adding hydrated aluminum oxide and silica glass or quartz to NaOH solutions in the modified 18-ml. Morey bomb. Two bombs were placed in each of the four electric resistance furnaces which were kept at a constant temperature by means of electronic temperature controllers described by Lazarus and Lawson (1947). The control thermocouples were located close to the furnace windings, whereas the measuring couple was inserted into a small hole bored 1 inch into the center of the bomb plunger. The temperatures were continuously recorded, by means of a chromel-alumel thermocouple and a Brown electronic strip-chart multipoint recorder. The temperatures were maintained at $\pm 1°$ of the temperature recorded in table 1. Before a run was quenched, the temperature was always checked with a Rubicon portable potentiometer and a standard thermo-

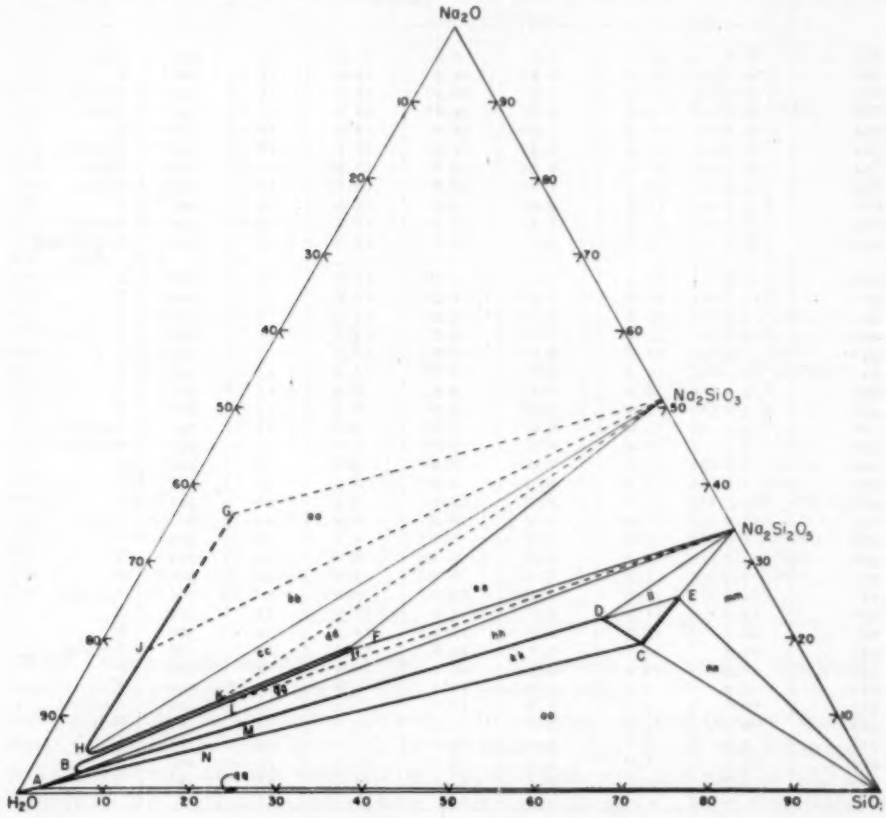

FIG. 2.—Polybaric saturation relations in the system H_2O-Na_2O-SiO_2 at 450° C.

TABLE 1

EXPERIMENTAL POINTS, H_2O-Na_2O-SiO_2-Al_2O_3 SYSTEM

RUN NO.	QUATERNARY SYSTEM* (PER CENT)			PROJECTION ON TERNARY PLANE† (PER CENT)		DURATION OF RUN (DAYS)	TEMP. (° C.)	ALUMINUM-CONTAINING CRYSTALLINE PHASE
	SiO_2	Na_2O	Al_2O_3	SiO_2	Na_2O			
	300° C.‡							
885	7.6	12.7	1.5	7.8	13.0	11	306	None
886	14.1	11.8	1.4	14.3	12.0	11	306	X
887	19.7	11.0	1.3	20.1	11.2	11	297	Analcite
888	28.6	9.8	1.2	29.1	10.0	11	297	Albite
892	15.8	11.7	1.4	16.1	12.0	12	302	X
893	17.5	11.4	1.3	17.9	11.7	12	302	Analcite
894	22.7	10.7	1.2	23.2	10.9	12	298	Albite
895	25.5	10.3	1.2	26.0	10.5	12	298	Albite
912	3.7	12.8	4.9	3.9	13.4	14	299	Y
913	18.9	10.4	4.4	19.7	11.2	14	299	Analcite
915	27.5	9.6	3.7	28.6	10.0	14	297	Anacite and albite
930	9.6	12.3	1.5	9.8	12.5	17	300	X
931	12.2	11.9	1.4	12.4	12.1	17	300	X
944	2.3	13.0	3.1	2.4	13.4	13	300	Y
945	4.6	12.7	3.0	4.7	13.1	13	300	X
946	7.4	12.3	2.9	7.6	12.7	13	297	X
947	10.7	11.9	2.8	11.0	12.2	13	297	X
904	3.4	8.1	1.7	3.5	8.3	13	301	X
905	5.8	7.9	1.6	5.9	8.1	13	301	X
906	9.5	7.6	1.6	9.7	7.8	13	297	Analcite
907	12.3	7.4	1.5	12.6	7.6	13	297	Analcite
964	8.0	7.7	1.6	8.2	7.8	20	298	X
965	1.7	8.2	1.7	1.7	8.3	20	298	X
966	14.9	7.1	1.5	15.1	7.2	20	301	?
967	18.0	6.9	1.4	18.2	6.9	20	301	Albite
968	2.5	7.9	3.3	2.6	8.2	20	302	Y
969	4.9	7.7	3.2	5.0	8.0	20	302	X
970	7.9	7.5	3.1	8.1	7.7	20	301	X
971	14.6	7.0	2.9	15.0	7.2	20	301	Analcite
956	13.8	11.5	2.8	14.2	11.8	12	300	X
957	16.2	11.0	2.7	17.1	11.3	12	300	X
958	19.4	10.7	2.6	19.8	11.0	12	308	Analcite
959	21.9	10.4	2.5	22.4	10.6	12	308	?
972	9.9	7.5	3.0	10.2	7.8	13	302	X
973	12.6	7.3	3.0	13.0	7.5	13	302	Analcite
920	0.0	13.2	3.2	0.0	13.6	13	301	None
921	3.8	12.7	3.0	4.0	13.1	13	301	Y
922	13.4	11.0	4.4	14.0	11.5	13	298	X
923	16.7	10.6	4.2	17.5	11.1	13	298	Albite
	450° C.							
926	17.6	10.1	5.8	18.7	10.8	7	450	X
927	16.2	9.3	10.6	18.1	10.4	7	450	Y
916	20.7	11.0	1.8	21.3	11.3	7	448	None
917	23.9	10.5	1.7	24.5	10.8	7	448	None
908	3.4	13.2	2.2	3.5	13.5	4	449	Y

* The components listed in these three columns, plus H_2O, equal 100 per cent.

† The components listed in these two columns, plus H_2O, equal 100 per cent.

‡ The volume of the bombs was 18 ml. In all runs made at 300° the bombs were filled to 10 ml. In all runs at 450° the bombs were filled to 7 ml.

TABLE 1—*Continued*

Run No.	Quaternary System* (Per Cent)			Projection on Ternary Plane† (Per Cent)		Duration of Run (Days)	Temp. (° C.)	Aluminum-containing Crystalline Phase
	SiO_2	Na_2O	Al_2O_3	SiO_2	Na_2O			
	450° C.—*Continued*							
909	6.5	12.8	2.1	6.7	13.2	4	449	X
900	13.8	11.7	1.9	14.4	12.2	5	448	X
901	25.8	10.2	1.7	26.4	10.5	5	448	Albite
902	10.0	12.0	4.0	10.7	12.7	5	445	X
903	9.2	11.0	9.0	10.7	12.7	5	445	Y
898	0.0	12.3	13.1	0.0	14.2	5	449	Y
899	9.6	11.4	10.6	10.7	12.7	5	449	Y
896	10.8	12.3	2.0	11.1	12.6	3	449	X
897	20.6	10.9	1.8	21.1	11.2	3	449	X
934	18.3	10.6	3.6	19.0	11.0	6	451	X
935	21.9	10.1	3.5	22.7	10.5	6	451	X
942	9.7	11.2	6.3	10.4	12.0	7	447	X
943	16.9	9.8	8.3	18.4	10.7	7	447	Y
948	18.8	10.9	1.8	19.3	11.2	8	447	None
950	14.8	11.5	1.9	15.3	11.8	8	447	X
949	24.5	10.1	1.7	25.1	10.4	8	450	Albite
951	25.1	9.7	3.3	26.0	10.0	8	450	Paragonite
962	3.3	12.5	4.2	3.4	13.1	7	447	Y
963	6.3	12.1	4.1	6.6	12.7	7	447	X
961	23.2	10.0	3.4	24.0	10.3	6	445	?
960	28.1	9.3	3.2	29.1	9.6	6	445	Albite
980	34.5	12.9	0.4	34.6	12.9	7	453	None
982	34.1	12.7	1.1	34.5	12.9	7	452	None
983	33.9	12.6	1.5	34.4	12.8	7	452	X—few mg.
975	6.9	7.9	4.5	7.0	8.1	7	455	X
976	22.1	6.6	1.9	22.4	6.7	7	452	Albite
977	24.2	6.4	1.9	24.7	6.5	7	452	Albite
889	31.3	9.5	1.6	32.1	9.7	7	449	Albite
890	17.0	11.4	1.9	17.6	11.8	7	452	X

couple. Owing to the unknown but constant thermal gradient between the thermocouple and the bomb interior, the estimated temperature error is ±5° C. In order to secure a uniform temperature throughout the length of the 12-inch-long tube of the furnaces, a thick (3/16-inch) copper tube was placed inside the alundum furnace muffle between the bombs and the furnace wall. The copper jacket aided in securing uniform heat distribution. The four furnaces were mounted on a frame which rocked through an arc of about 90° at the rate of 14 cycles per minute. The bombs were quenched with the equipment previously described (Friedman, 1950).

In contrast to the ternary system (Friedman, 1950; Tuttle and Friedman, 1948), where runs of 2 days at 300° C. and 1 day at 450° C. were of sufficient duration to secure equilibrium, it was found that runs of 10–14 days at 300° C. and 4–5 days at 450° were necessary when Al_2O_3 was added. The difficulty in securing equilibrium in this system led Königsberger and Müller to conclude that equilibrium is rarely reached below 400° C. in hydrothermal experiments.

After the bombs had been quenched

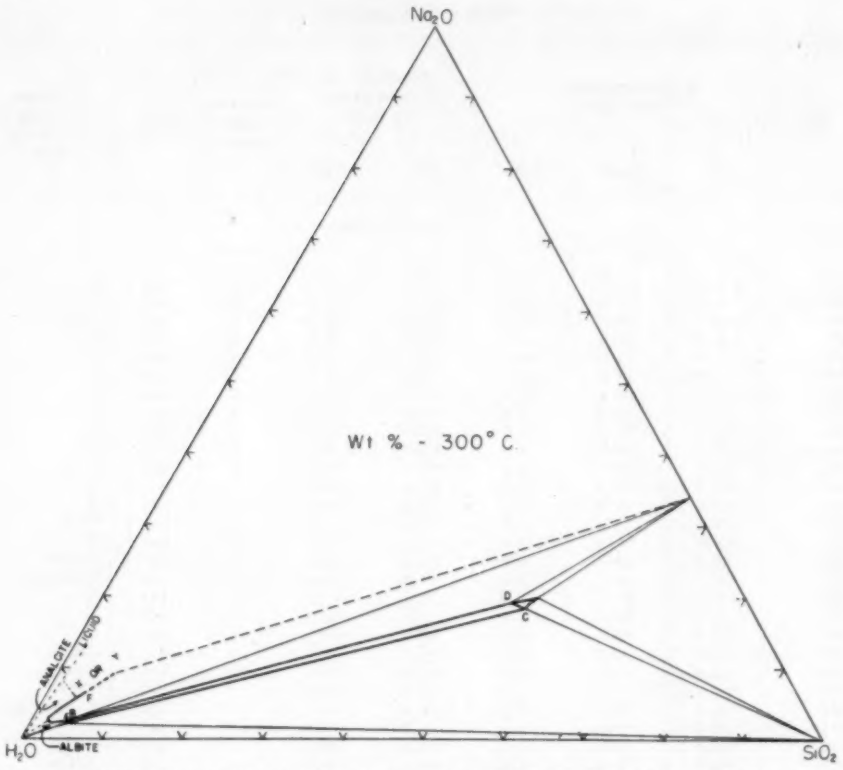

FIG. 3*A*.—Polybaric equilibrium relations in the system H_2O-Na_2O-SiO_2-Al_2O_3 at 300° C. A projection on the ternary plane of the 1.2–1.7 per cent Al_2O_3 section through the H_2O-Na_2O-SiO_2-Al_2O_3 tetrahedron at 300° C.

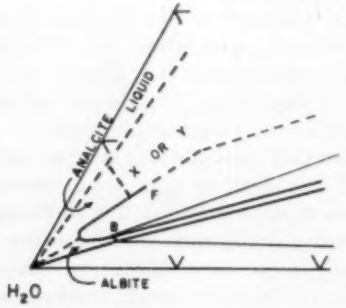

FIG. 3*B*.—Enlarged section of the H_2O corner of fig. 3*A*.

and opened, they were washed out by running a slow stream of hot water through them for 8–24 hours. The water dissolved the soluble glasses and crystalline materials, such as sodium disilicate and metasilicate. The residue remaining after this treatment was dried, using alcohol and acetone, and X-ray powder diffraction photographs were then taken. The iron radiation used was produced from a Philips water-cooled tube operating at 45 kv. and 10 Ma. and filtered through a manganese dioxide filter. Both 57.3-mm. and 114.59-mm. diameter Philips powder cameras were used.

A description of the materials employed in the investigation of the ternary system will be found in the paper by Tuttle and the author (1948). The aluminum hydroxide used was "Aluminum hydroxide, Bakers Analyzed." The water content was determined by measuring the loss in weight of samples heated to constant weight at 1,000° C. The analyses show the $Al_2O_3 \cdot XH_2O$ to contain 34.71 per cent H_2O.

RESULTS

In order to help determine the position of the stability fields of analcite and albite, selected crystals of albite from Amelia County, Virginia, were placed in a bomb, together with NaOH and silica glass. It was decided to fix the initial NaOH concentration for the first series of runs. A value of 14 per cent Na_2O was chosen for the first "traverse." At 300°, as the amount of silica glass was increased from 0 to 3.0 g., it was noticed, first, that albite was altered to an unknown phase, which will be designated as "X" for the present, then to analcite, and, finally, the albite remained unaltered as the amount of SiO_2 added approached the quartz saturation boundary.

In all further experiments the technique of placing definite amounts of aluminum oxide, silica, and sodium hydroxide solution in the bombs was employed. In order further to simplify the work, the amount of Al_2O_3 added was initially fixed at 0.3 g. of hydrated alumina (65 per cent Al_2O_3) and the Na_2O concentration at 14 per cent. Table 1 shows the results of this traverse, as well as another made with 0.6 g. of hydrated Al_2O_3. Runs were also made with a more dilute NaOH solution, 7 per cent Na_2O.

As was pointed out in the discussion of the 300° C. isotherm in the ternary system, the only liquids which can exist at this temperature are those whose compositions lie to the left and below the curve *FBDC* H_2O (fig. 1). Therefore, if it is assumed that the addition of a few per cent of Al_2O_3 will not alter the situation greatly, it can be seen that the phases indicated in figures 3 and 4 will be in equilibrium with liquids of the compositions indicated. This will be true for Al_2O_3 concentrations up to about 8 per cent. No runs were made with concentrations higher than this.

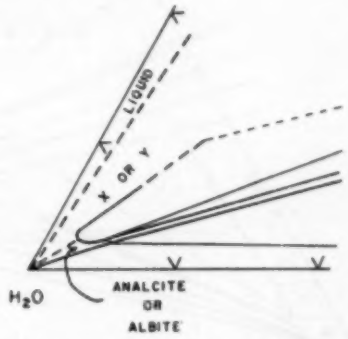

FIG. 4.—Polybaric equilibrium relations in the system H_2O-Na_2O-SiO_2-Al_2O_3 at 300° C. A section of the projection on the ternary plane of the 2–4 per cent Al_2O_3 section through the H_2O-Na_2O-SiO_2-Al_2O_3 tetrahedron at 300° C. Pressure will influence the analcite-albite stability relations.

The situation at 450° C. is more complex. As can be seen from figure 5, the stability field above the albite field is unoccupied by a solid phase; the Al_2O_3 dissolves in the liquid. This field would probably be occupied entirely or in part by analcite, provided that the H_2O pressure was high enough. The important feature petrologically is that a liquid exists which can dissolve a fairly large amount of alumina. Upon cooling to 300° C., this alumina-containing liquid could yield albite and/or analcite. Although this is true of liquids of fairly nar-

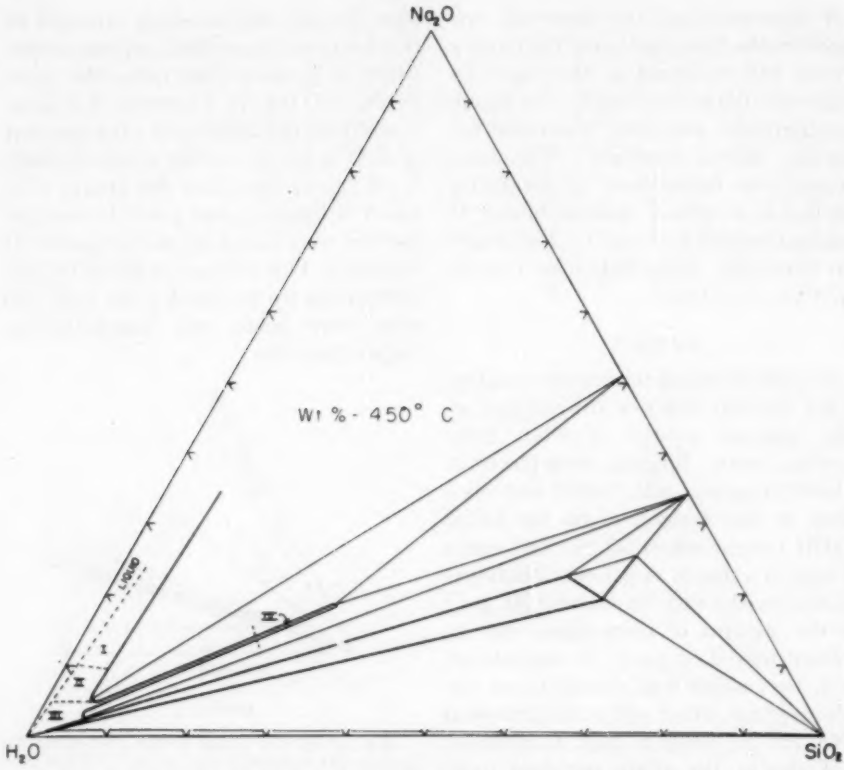

FIG. 5*A*.—Polybaric equilibrium relations in the system H_2O-Na_2O-SiO_2-Al_2O_3 at 450° C. A section of the projection on the ternary plane of the 1.5–6 per cent Al_2O_3 section through the H_2O-Na_2O-SiO_2-Al_2O_3 tetrahedron at 450° C. Field *I* is occupied by phase X or Y, depending upon the SiO_2-Al_2O_3 ratio, the high-silica end favoring the stability of X. Field *II* is occupied at high H_2O pressure by X and at low pressure by a solution only. Field *III* is occupied at intermediate pressure by albite and at low pressure by a solution. Presumably, it will be occupied by analcite at very high pressures. Field *IV* is occupied by albite.

row concentration range, this range may be extended by the addition of other components and by a change in pressure.

THE PHASE X

X-ray powder diffraction pictures of the phase X did not resemble pictures taken of samples of any of the known sodium aluminum silicates—paragonite, ussingite, naujakasite, jadeite, natrolite, analcite, albite, nephelite, carnegieite, or hydronephelite.[3]

A single crystal X-ray picture taken by A. J. Frueh by the Weissenberg method shows the crystal to be hexagonal. Its typical habit is a hexagonal prism terminated by basal pinacoids with a length-to-length-thickness ratio of 5:1. Its indices as determined by the aid of the double variation method are $\epsilon = 1.495$, $\omega = 1.502 \pm 0.002$. A density determi-

[3] Samples of hydronephelite obtained from Ward's Natural Science Establishment, Rochester, N.Y., as well as those from the Chicago Natural Science Museum proved to be mainly natrolite.

nation made on several large (1-mm.) crystals with the aid of the Berman balance gave a density of 2.36 ± 0.03.[3]

Several chemical analyses were made, but these were complicated by the difficulty of securing samples of sufficient size, free from contamination by glass. The samples chosen for analysis were seldom over 0.2 gm., and therefore the results of the analyses are somewhat in doubt. The formula of phase X was derived by first fixing the SiO_2-H_2O mole ratio and then considering possible formulas consistent with the experimental results. Table 2 gives an average of three chemical analyses of this phase. The empirical composition is $13Na_2O \cdot 9Al_2O_3 \cdot 22SiO_2 \cdot 12H_2O$. The formula given is believed to be the best "fit" for the analytical results. However, this formula is still very tentative, and more work needs to be done to fix its composition definitely.

A dehydration curve shows that this material probably does not have a zeolite-type structure in which the water occurs interstitially and is easily reversibly removed without destroying the basic structure.

An attempt to synthesize a glass of phase X composition, starting with Na_2CO_3, SiO_2 glass, and hydrated Al_2O_3, did not meet with much success. The glass proved to be hygroscopic, and it was difficult to keep it on composition.

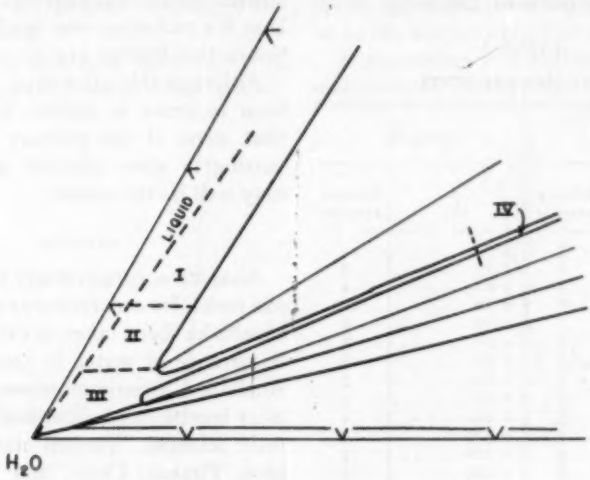

FIG. 5*B*.—Enlarged section of the H_2O corner of fig. 5*A*

TABLE 2

ANALYTICAL RESULTS

PHASE	PER CENT	
	X	Y
Na_2O	25.6	25.4
Al_2O_3	27.5	32.0
SiO_2	38.6	36.8
H_2O	6.8	6.6
Total	98.5	100.8

Sodium oxide loss could not be accurately ascertained because the glass picked up H_2O during the crushing and grinding necessary to its homogenization.

[3] G. J. Wasserberg, personal communication.

THE PHASE Y

As in the previous case, X-ray powder diffraction pictures of phase Y did not check with those of any known sodium aluminum silicate. Although it appears isotropic under the microscope, single-crystal X-ray pictures taken by A. J. Frueh prove it to be hexagonal. It often crystallized in thin six-sided basal plates. Its index is $1.4\varsigma8 \pm 0.002$ and its birefringence is about 0.002. Its chemical analysis is given in table 2, and the phase has a composition corresponding to $28Na_2O \cdot 19Al_2O_3 \cdot 42SiO_2 \cdot 24H_2O$. Dehydration curves indicate that this substance probably does not have a zeolite-type structure.

TABLE 3

X-RAY MEASUREMENTS

Phase Y		Phase X	
d (Å)	Relative Intensity	d (Å)	Relative Intensity
3.25	5	3.57	1
2.32	2	3.23	8
2.10	2	2.81	4
1.92	10	2.40	10
1.64	1	2.16	6
1.53	4	1.91	8
1.41	7	1.71	8
1.325	3	1.65	7
1.257	4	1.60	3
1.203	5	1.40	4
1.120	1	1.329	5
1.062	3	1.260	3
1.022	2	1.219	2
1.007	3	1.100	2
		1.087	2
		1.074	3
		1.057	4
		1.040	2
		1.027	3
		1.019	1
		1.004	4

The formulas of X and Y can be derived from $3Na_2O \cdot 2Al_2O_3 \cdot 6SiO_2 \cdot 3H_2O$ by substituting Al_2O_3 and Na_2O for 8 per cent (by weight) of SiO_2. The resulting compound corresponds to X. Substitution of Al_2O_3 and Na_2O for another 8 per cent of SiO_2 yields the compound Y. Because of the complexity of the molecule, a change of less than 1 per cent in the analytical results will make a considerable difference in the calculated formula.

Table 3 gives the spacings of the X-ray powder diffraction patterns of X and Y. Iron Kα radiation was used in conjunction with a Philips 114.59-cm. camera.

Although this substance, Y, has never been reported in nature, it is believed that some of the primary analcite occurring in some alkaline igneous rocks may well be this phase.

ANALCITE

Analcite occurs in many types of igneous rocks. Its occurrence as amygdules in basalts has been taken as evidence for the occurrence of water in basalt magmas. Analcite is a common secondary mineral after leucite, nepheline, and albite or albitic feldspar. Various authors (Lindgren, Pirsson, Cross, and Washington; see Clarke, 1924, p. 452) have suggested that analcite in some hypabyssal rocks is of primary origin. Scott (1916) has used the following criteria to prove the primary nature of analcite in igneous rocks:

> A high degree of idiomorphism of the pyroxenes and amphiboles of a rock so rich in analcite as lugarite is against the secondary nature of the last named mineral. It is most improbable that either feldspar or nephelite could be so corroded and replaced as to have completely disappeared, while the ferromagnesian minerals show no trace of alteration whatsoever.

An analysis of figure 6 (after Yoder, 1950) shows that analcite can exist up to about 580° C. if a H_2O pressure of at least 30,000 p.s.i. is present. According to Bowen and Tuttle (1949), the highest temperature at which serpentine can exist is 500° C. If the olivine contains as little as 10 per cent fayalite, the upper existence temperature of serpentine will be lowered about 80° C., whereas olivine

containing 52 per cent fayalite resists serpentization at 295° C. and 15,000 p.s.i. water pressure. Therefore, analcite and olivine can coexist in the temperature range 500°–600° C. at considerable H_2O pressure. This temperature interval will be extended as the iron content of the olivine increases.

Albite is a common constituent of many metamorphic rocks which recrystallized under rock loads of 10,000–15,000 p.s.i. For albite to be stable it is necessary that either the water pressure be equal to the load pressure and the temperature be above 500° C. or that the water pressure be fairly low (below 3,000 p.s.i.), in which case the temperature can be in the neighborhood of 250° C.

The occurrence of authigenic albite in sediments of Tertiary age and older and

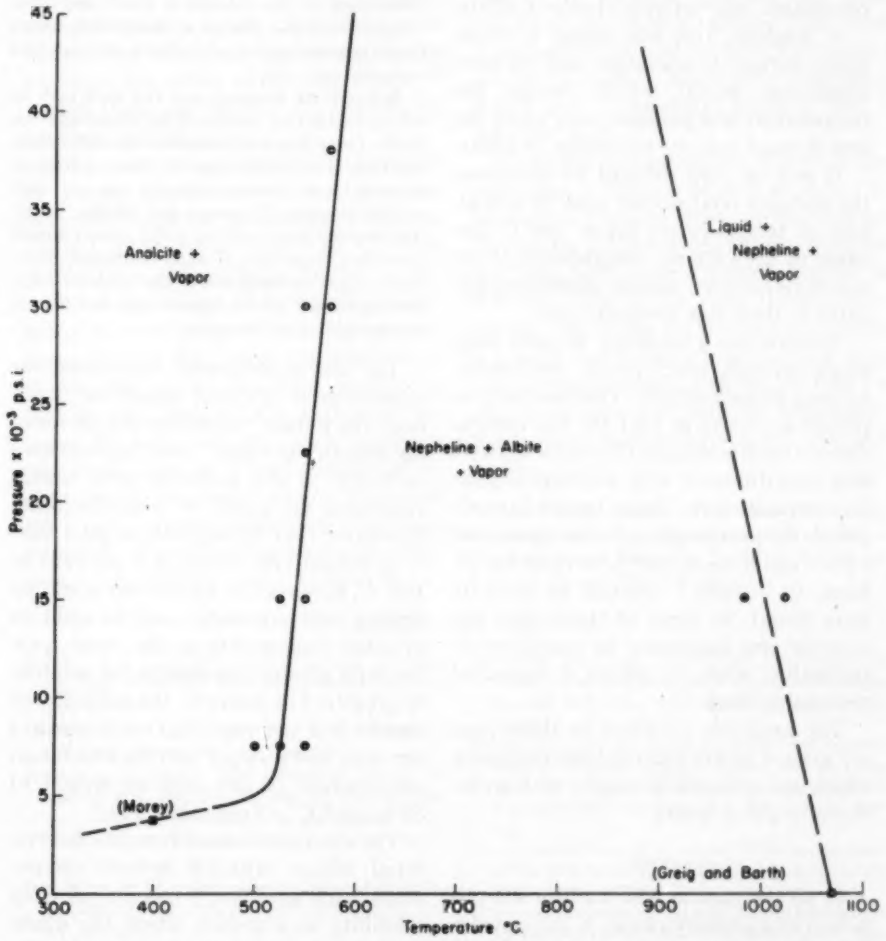

FIG. 6.—Temperature-pressure diagram for the analcite-albite nepheline equilibrium. Original from Hatten S. Yoder (1950).

its apparent absence from more recent sediments may be explained in either of the following ways:

1. Albite is stable under surface conditions of temperature, pressure, and composition; but analcite, which has been observed growing authigenically in recent muds, forms metastably. This metastable growth of analcite will be discussed later. Metastable analcite will, under surface temperature and pressure conditions, convert very slowly to albite.

2. Analcite, but not albite, is stable under surface temperature and pressure conditions. Burial, which changes the temperature and pressure, may cause the first-formed analcite to change to albite.

It will be very difficult to determine the stability relations for analcite and albite at temperatures below 300° C. because of the extreme sluggishness of the reactions between sodium aluminum silicates at these low temperatures.

Analcite has a tendency to form large single crystals, which persist metastably for long periods of time. This tendency to persist accounts in part for the contradictory results obtained by early workers who experimented with mixtures similar in composition to those herein investigated. In practically all runs quenched before equilibrium had been established, large (0.1–3-mm.) crystals of analcite were found. In some of these runs the analcite was beginning to transform or redissolve, while in others it appeared reasonably fresh.

The analcites obtained in these runs are always nicely formed icositetrahedra which are optically isotropic, with an index of 1.486 ± 0.002.

ALBITE

In all the runs in which albite was obtained as a primary phase, X-ray powder diffraction photographs of the crystals show that the albite is the high-temperature form described by Tuttle (1950). Albite twinning or a combination of pericline and Carlsbad twinning is common in the synthetic material.

THE GRANITE PROBLEM

It has been stated in the literature (Ramberg, 1949):

> However, we have good experimental as well as field reasons for believing that magmatism is confined to temperatures above 600°–900° C. (depending on the content of water and other "volatiles" in the silicate system). Only above these temperatures should silicate minerals and melt coexist.
>
> Below these temperatures the melt may be substituted for by saturated but dilute aqueous fluids. These saturated solutions should contain less than 1 or 2 per cent of silicates because common rock-forming minerals are not very soluble in water (Ingerson and Morey, 1937). On the other hand, silicate melts cannot absorb more than 10 per cent of water (Goranson, 1931, 1936, 1937): consequently, the system: rock-making silicate melts—water does not form a continuously miscible series.

The above statement concerning the experimental evidence should be qualified. The phrase "solubility of rock-forming minerals in water" must be examined carefully. If the solubility of a simple substance like quartz is being discussed, it is found that its solubility in pure water is indeed low—about 0.1 per cent at 300° C. However, in nature one is seldom dealing with pure water, and the addition of other components to the water, particularly alkalis, can change the solubility greatly. For example, the solubility of quartz in 2 per cent Na_2O solution is 4 per cent, and a 10 per cent Na_2O solution can contain 30 per cent by weight of SiO_2 (300° C.) (Friedman, 1949).

The situation is more complex if a material which contains several components, such as albite, is considered. Only solubility in a system where the solute can exist as a primary phase can be discussed. The solubility of albite in water,

therefore, has no meaning until temperatures and pressures are reached where albite can crystallize from water (fig. 6). However, the solubility of albite in a solution containing several per cent of Na_2O and saturated with quartz can be discussed, although such a discussion would have little meaning. The important fact, geologically speaking, is that one can have a solution at relatively low temperature (450° C.) which contains components in solution that are capable of yielding rock-forming minerals. For example, a solution of *III* (fig. 5) can, if cooled from 450° to 300° C., deposit albite and quartz.

The concept of immiscibility in liquid of granite-plus-water composition has been used to prove that a granite magma cannot exist, below 650°–700° C. This would be a serious blow to the proponents of the theory of the magmatic origin of granites because there is some evidence to show that many granites formed below 500° C. As has been shown by Tuttle (1948) and by the author in this paper, the lower temperature of existence of a liquid capable of producing the minerals found in a granite will be lowered if the liquid contains alkali in excess of that necessary to produce a granite. In other words, the granite-water system is replaced by a granite-water-alkali system.

The main evidence for the existence of a granite-water system is the existence of rhyolite flows. Rhyolite has a granite composition and is obviously a rapidly solidified lava. In this case excess alkali cannot be found. Many geologists have reasoned as follows: The coarse-grained gabbros have the same bulk chemical composition as do basalts. Therefore, a magma of basaltic composition (plus volatiles) can yield a gabbro. This view is supported by field evidences of basalts becoming coarse-grained with increasing depth and occasionally grading into a gabbroic rock.

However, one important fallacy in the argument is the lack of field evidence to show that rhyolite grades into granite. Therefore, I believe that some granites can have been formed from a magma of different composition than rhyolite plus water. The excess alkali remaining after a granite has formed could escape, e.g., into pegmatites and eventually find its way to the ocean, or into the metasomatized rocks surrounding many granitic bodies.

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GEOTHERMOMETRY OF SOME PEGMATITE MINERALS OF HYBLA, ONTARIO[1]

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ABSTRACT

The development of new techniques for the rapid measurement of the temperature of deposition of pyrite and the degree of filling of two-phase fluid inclusions has made it possible to determine temperatures and pressures of deposition of hydrothermal minerals. These techniques are applied to some of the minerals from a system of pegmatite dikes. Pressures existing in the solutions at the time of deposition of pyrite have been calculated and found to be of the order of 3,000 bars. Temperatures of crystallization of pyrite, quartz, fluorite, and oligoclase have been found in the range 450°–550° C. Anomalous decrepitation of calcite is discussed.

INTRODUCTION

Geologists engaged in the study of pegmatites have usually been content to make estimates of the conditions of temperature and pressure existing at the time of crystallization in the solutions from which the various minerals crystallized. However, with the exception of a few fixed points on the temperature scale, the majority of these estimates are perforce little more than intelligent guesses. One of the fixed points, namely, that at which the inversion of quartz from the α- to the β-modification takes place, has proved to be of extraordinary assistance in locating pegmatites within the general temperature sequence for igneous rocks as a whole. It was demonstrated particularly by Bastin (1910) that some of the quartz in graphic granite crystallized initially above the inversion temperature, which at atmospheric pressure is near 573° C.,[2] whereas quartz crystals lining miarolitic cavities in the same deposit showed evidence of having been formed below the inversion temperature. By establishing a paragenesis for the minerals of the deposit, including quartz, based on cross-cutting or contact relationships, it is possible to arrange them in two groups: those which crystallized at temperatures higher than the quartz inversion temperature and those formed at lower temperatures. Unfortunately, it is seldom possible to be much more specific with this method.

New techniques in geothermometry now make possible a closer approximation of the temperatures and pressures of formation of some hydrothermal minerals. Although these techniques do not always provide a unique answer or one of extreme accuracy, they assist very greatly in outlining the mineralogical history of a deposit. If it is assumed that the mineral sequence came about during a fall in temperature, the paragenesis of the minerals may be determined.

The procedure used by the author to determine the temperatures and pressures of crystallization is twofold. It consists essentially of determining the degree of filling of two-phase fluid inclusions by the decrepitation method, in conjunction with the direct measurement of the pyrite crystallization temperature with the Smith pyrite geo-

[1] Manuscript received March 31, 1950.

[2] The inversion temperature of quartz is raised with increase in pressure, the value being 636° C. at a pressure of 2,900 bars (from data by R. E. Gibson, 1928, p. 1197).

thermometer. Calculations based on the degree of filling of the fluid inclusions in pyrite, the direct temperature measurement on a single specimen of that mineral, and temperature/pressure/specific volume relationships for water result in a value of pressure. With certain assumptions, this may be applied to other minerals in the deposit, and decrepitation tests made on these will determine the degrees of filling of their respective inclusions. Corrected values of temperature can then be calculated from these with the aid of temperature/pressure/specific volume curves, using the pressure value obtained from the pyrite data.

In the study of a series of granite pegmatites which cut the Grenville metasediments near Bancroft, Ontario, the writer used these new techniques in geothermometry. Material was collected from a number of related pegmatites, particular attention being paid to the old MacDonald feldspar quarry, where excellent suites are available. Care was taken in the field to select samples as fresh as possible; pyrite was collected wherever observed. Fortunately, pyrite is present in all the larger deposits.

TEMPERATURE-PRESSURE MEASUREMENTS AND CALCULATIONS

In the laboratory each of the minerals was hand-picked to ensure freedom from contamination by other minerals. Only those known or suspected to be of hydrothermal origin were considered, the use of fluid inclusions in geothermometry being based on the assumption that the mineral in question crystallized from a solution essentially aqueous. A thick "thin section" was made of each of the nonopaque minerals and was examined under a high-power microscope for the presence of two-phase fluid inclusions. In the making of the thin sections it was found advisable to avoid using balsam as a mounting medium because the heat necessary to cure the balsam destroyed some of the inclusions. It was convenient for grinding to cement the mineral to the glass with Glyptal or Duco and to use index oil under the cover glass. The fluid inclusions may readily be recognized, and the observation of Brownian or gravitational movement of the gas bubble furnishes positive proof of their identity. Furthermore, it was possible, after some practice, to estimate roughly the degree of filling of the inclusions and to predict within 50° C. the temperature at which the liquid in the inclusions would fill the space available and above which the mineral would decrepitate.

All the samples of pyrite were tested with the pyrite geothermometer described by Smith (1947), the procedure being to make a large number of readings (at least fifty) on each specimen, to plot a scatter diagram, and to take the temperature corresponding to the peak or peaks as the real temperature of crystallization of the pyrite.

The specimens were prepared for decrepitation in the following manner. After hand-picking, each mineral was crushed and screened, the grain size being dictated by experience and by an estimate made while examining the material with the microscope. Most of the fluid inclusions in the quartz were found to be relatively small, and, because previous experience has shown that coarse grains of that mineral tend to produce small anomalies on the decrepitation curves, all the quartz was crushed to −40 +80 mesh. With regard to pyrite, experience showed that the most satisfactory curves were obtained with particles sized at −10 +40 mesh.

Calcite was present in all the deposits;

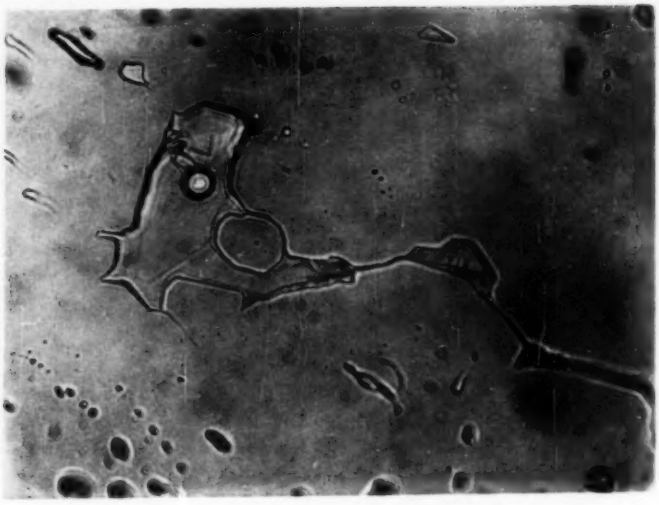
and, because its presence as a contaminant, even in minute fractures, results in anomalous decrepitation, all the minerals were treated with HCl. In addition, the silicates were removed from the pyrite with HF. After acid treatment the samples were well washed and dried with acetone and gentle heat.

Decrepitation runs were made on 5-gm. samples of the prepared minerals, following the procedure outlined by Peach (1949). In order to keep a check on the apparatus and upon the results, several runs were made with material from each specimen, the smoothest curve obtained in each case being reserved for interpretive measurement. The decrepitation temperatures, corresponding to the inflection points, were obtained by graphical analysis of the curves in the simplest way. If at this stage preliminary examination of a curve suggested that greater resolution would be obtained with different settings of the controls on the apparatus or by use of a different grain size, the procedure was repeated until the best possible curve was obtained. In some cases even the best possible curve was obscure as a result of recrystallization or contamination of the sample; hence the readings are not all of the same degree of accuracy. This, more than any other factor, probably accounts for the variations.

In most cases the presence of secondary inclusions was detected. These had already been observed in the thin sections and the probable temperature of decrepitation estimated. Inclusions of this type may be recognized under the microscope by the relatively small volume of the bubbles and by the fact that they tend to be arranged in planes within the mineral. They are distinguished from primary inclusions by the random distribution and lower degree of filling of the latter. These secondary inclusions are considered to have been formed by partial recrystallization of the mineral along fractures or cleavages through the agency of later circulating solutions.

Theoretically the ideal decrepigraph should show a very sharp inflection point at the decrepitation temperature, corresponding to the temperature of complete filling of the inclusions by the liquid phase. Unfortunately, this is very rarely realized. Typical decrepigraphs have a very pronounced "toe" to the curve, corresponding to some spurious decrepitation occurring before the temperature of complete filling is reached. This toe or "toe effect" often makes the interpretation of the curves difficult. Such a feature might be produced if the mineral did not have a single crystallization temperature but, instead, a temperature range. This, however, seems unlikely because it is probable that the range of temperatures of crystallization of different parts of a specimen, such as those used in the present study, would be too small to be detected by the technique. Certainly, the variation between different samples of one mineral, from the same deposit, is very much less than is required by this theory. The answer may lie in some of the characteristics of fluid inclusions observed in thin section.

Inclusions are commonly seen which have a smaller vapor to liquid ratio than normal for the particular specimen. These are associated with inclusions having ratios larger than normal, and commonly the remains of threadlike connections can be seen between the two types (pl. 1, *A*). In some cases this connection appears to have been partially obliterated, possibly by later crystallization, and it is suggested that, if this closure took place at a temperature slightly lower than that of formation and after a



A

B

Two-phase fluid inclusions

vapor bubble had already appeared, then one inclusion of each pair has within it a bubble of vapor which normally would have been partially shared between the two. Thus the more completely filled inclusion will decrepitate at a temperature which will be a function of that at which it was sealed off from its neighbor.

The results obtained, both with the pyrite geothermometer and from analysis of the decrepigraphs, are reproduced in table 1. The procedure for calculating the pressure in the solutions at the time of crystallization is based upon the relationships between pressure, temperature, and specific volume of aqueous solutions. The decrepitation temperature, with suitable correction for "overshoot" (which is the experimentally determined difference between the true temperature of complete filling of the inclusions and the temperature of decrepitation and is about 20° C. for quartz or 15° C. for pyrite), corresponds to the temperature of complete filling of the inclusions by the liquid phase and therefore to one of a series of specific volume curves on a chart, such as that reproduced by Scott (1948), which shows the variation in specific volume with temperature and pressure. The point on this curve corresponding to the temperature of formation, indicated by the pyrite geothermometer, will thus also correspond to the pressure in the solution at the same time.

The pressures of deposition were determined for each of the specimens of pyrite studied by following this procedure. For example, in table 1, specimen 1, the decrepitation temperature was found to be 306° C. If the overshoot is 15° C., the temperature of complete filling of the inclusions will be 291° C. On Scott's chart this corresponds to a specific volume of nearly 1.4 cm^3/gm. Following the curve of 1.4, it will be seen to intersect the temperature 478° C., found from the pyrite geothermometer, at a pressure corresponding to 3,000 bars. This, then, is taken as the pressure of deposition of the pyrite.

If it is assumed that this is the pressure of formation of the other minerals in the deposit, then their temperatures of deposition may be determined by finding, as before, the specific volume curve corresponding to the temperature of complete filling of the inclusions and by reading from it the temperature corresponding to that pressure. Thus in the case of quartz, table 1, specimen 3, the decrepitation temperature is 348° C., overshoot 20° C., temperature of filling 328° C. This indicates a specific volume of a little over 1.5 cm^3/gm, which at 3,000 bars corresponds to a temperature of 530° C. All this is based on the assumption that the pyrite is very closely related to the other minerals of the deposit, which in the present case seems to be justifiable on the basis of field evidence.

Although calcite was present in almost all the pegmatites sampled, no temperature-pressure data are recorded for this mineral. It was suspected during the present study that anomalous decrepitation conditions existed in some of the carbonates because a decrepitation temperature of approximately 265° C. was

PLATE 1

A, Two-phase fluid inclusions in quartz from locality No. 9. ×100. The large inclusion is multiple and shows threadlike connections between the chambers.

B, Two-phase fluid inclusions in oligoclase from locality No. 7. ×200. The dark spot in the larger inclusion is the gaseous phase. The inclusion is multiplanar, only part of it lying in the plane of sharp focus.

observed in all specimens of calcite tested, irrespective of origin. The synthesis of calcite in a high-pressure autoclave under controlled conditions confirmed these suspicions because the artificial crystals of calcite showed a normal decrepitation within 5° C. of the calculated temperature, followed by a second decrepitation commencing near 265° C. and similar to that in the natural min-

TABLE 1

RESULTS OF SOME OF THE GEOTHERMOMETRIC TESTS MADE

Specimen No.*	Mineral Species	Decrep. Temp. (° C.)	Pyrite Geotherm. Reading (° C.)	Pressure (Bars)	Temperature of Deposition† (° C.)
1	Pyrite	306	478	3,000	478
2	Pyrite	358	650	3,000	650
3	Quartz	348	.....	3,000	530
4	Quartz	152	Secondary inclusions pressure unknown		
5	Quartz	320	.....	3,000	510
6	Quartz	312	.....	3,000	480
7	Oligoclase	295	.....	3,000	455
8	Pyrite	307	498	2,800	498
9	Quartz	148	Secondary inclusions pressure unknown		
9	Quartz	328	.....	2,800	505
10	Pyrite	292	450	2,800	450
11	Quartz	116	Secondary inclusions pressure unknown		
11	Quartz	305	.....	2,800	450
12	Quartz	128	Secondary inclusions pressure unknown		
12	Quartz	305	.....	2,800	450
13	Pyrite	340	505	2,900	505
14	Quartz	158	Secondary inclusions pressure unknown		
14	Quartz	310	.....	2,900	460
15	Pyrite	.....	490	Insufficient for decrepitation	
No pressure calculated for this deposit; a pressure of 2,900 bars assumed					
16	Quartz	330	.....	2,900 (assumed)	515
17	Fluorite	80	Secondary inclusions pressure unknown		
17	Fluorite	280	.....	2,900 (assumed)	430
18	Pyrite	317	482	2,800	482
19	Quartz	345	.....	2,800	525
20	Quartz	140	Secondary inclusions pressure unknown		
20	Quartz	320	No pyrite, pressure unknown		

* List of specimens follows:

No.
1. Pyrite from main pit at MacDonald feldspar mine.
2. Pyrite from small pit at MacDonald mine.
3. Smoky quartz from main pit at MacDonald mine.
4. Band of secondary inclusions from smoky quartz, main pit, MacDonald mine.
5. Massive quartz, main pit, MacDonald mine.
6. Quartz crystals from vug center of main pit at MacDonald mine.
7. Oligoclase from vug, small pit at MacDonald mine.
8. Pyrite from small pit lot 27, concession VII, Monteagle Township.
9. Quartz from same pit.
10. Pyrite from Genesee No. 2 pit.
11. Quartz in contact with pyrite Genesee No. 2 pit.
12. Quartz lining vugs Genesee No. 2 pit.
13. Pyrite filling fractures in Microcline Thompson pit.
14. Quartz from Thompson pit.
15. Pyrite from small pit lot 20, concession VI, Monteagle Township.
16. Quartz from same pit.
17. Fluorite ditto.
18. Pyrite from pit lot 21, concession VII, Monteagle Township.
19. Quartz from same pit.
20. Quartz from Woodcox mine dump. No pyrite available.

† Values given for "Temperature of Deposition" include pyrite geothermometer readings and determinations from $p/v/t$ curves partially dependent on pyrite geothermometer readings. They are true only within the limits of error of the instrument.

eral. It appears, therefore, that the results obtained from calcite were not reliable. No satisfactory explanation has been found for the anomalous condition in calcite, which nevertheless seems to be a true decrepitation, in that minute explosions are produced by the breaking-out of fluid inclusions.

DISCUSSION OF RESULTS

It has been necessary to make a number of basic assumptions, the validity of which affect the accuracy of the final results. It is assumed that the $p/v/t$ curves for aqueous solutions are essentially the same as those for pure water. Although the presence of a solute undoubtedly does alter the shape of the curves, the effect is most likely to be small. It is furthermore assumed that the pressure existing in the solutions at the time of formation of the various minerals remained constant. In the case of pegmatites this may not be very far from the truth, inasmuch as the major component of pressure must have been the rock load, a factor not likely to change greatly during the time of initial crystallization. However, as the reworking which gave rise to the secondary inclusions detected in most of the minerals must have taken place considerably later than the initial crystallization, no correction for pressure is made, and the decrepitation temperatures are reported unmodified. Errors in the calibration of the pyrite geothermometer undoubtedly do exist and, as such, will shift the absolute values of temperature up or down the scale by the amount of the error, which may be of the order of $\pm 20^\circ$ C. These errors will not alter the values of temperature relative one to another but will, however, govern the absolute values of temperature and pressure in table 1, which are in part dependent upon them.

Values of temperatures and pressures of formation of quartz, pyrite, plagioclase, and fluorite were determined. Attempts were made, without success, to obtain decrepigraphs from other minerals present both in the pegmatites and in the wall rock, such as titanite, augite, scapolite, and microcline. Thin-section study of these minerals failed to reveal the presence of fluid inclusions, and it may be that the lack of decrepitation can be accounted for simply by the absence of such inclusions. Good decrepigraphs have been recorded with some of these minerals from other deposits.

The results recorded in table 1 show a remarkable constancy in the values calculated for pressure, even with a fairly wide scatter in the measured temperatures of formation of the pyrite. This might be expected, however, as it is most likely to have been a simple function of the rock-load pressure, and, because the deposits studied are clustered within a small area at the same relative elevation, the rock load must have been very nearly constant. The variations in pressure as found may not be real but due to experimental error. Similarly, the variation in corresponding temperatures for one mineral is of small order, although these temperatures differ, sometimes considerably, from those of similar deposits elsewhere. Again, this may be due to the closeness of the deposits one to another and the possible equalizing effect of deep burial.

Specimen No. 7 consisted of an aggregate of oligoclase crystals, the lining of a vug at the MacDonald feldspar mine. The decrepitation of this material was good, a distinct inflection point, which represents primary inclusions, being present on the curve. Thin-section study of the feldspar revealed two-phase fluid inclusions having the rough form of negative crystals and all the appearance of being primary (pl. 1, *B*). Conspicuously

absent were the zones and planes of fracturing filled with secondary inclusions, which cut the massive feldspars of the dike and the minerals of the wall-rock gneiss. This seems to indicate that the sodic plagioclase, at least, continued to crystallize as late as the hydrothermal stage of the pegmatite, a suggestion which receives support from some of the field and textural evidence seen in the minerals of the dike.

The measured decrepitation temperatures of primary fluid inclusions and the calculated deposition temperatures of the above pegmatitic minerals are notably different from those suggested by Ingerson (1947), who studied several specimens of pegmatitic quartz. However, the measured decrepitation temperatures of the secondary fluid inclusions agree with Ingerson's heating-stage results.

CONCLUSIONS

The results of the present study show that some of the hydrothermal minerals, particularly quartz, pyrite, fluorite, and oligoclase, crystallized within a restricted range of pressure and temperature.

If the constancy of pressure is assumed to mean that the major component was that of the overlying rock load, then a tentative depth of burial for the pegmatites in the area studied, at the time of crystallization of the pyrite, may be taken at 6.5–7.5 miles. This calculation is based on an average specific gravity of 2.5 for the overlying rock.

With the exception of one generation of pyrite from a small subsidiary dike at the MacDonald feldspar quarry, the range of temperatures of deposition of the minerals examined lies within the limits of 450° and 550° C. No high-temperature quartz was found, and it is possible that any of that mineral which may have crystallized at temperatures of 600° C. or higher did not originate in a hydrothermal solution and hence would not be detected by the decrepitation technique.

Secondary inclusions were found in all the samples of quartz and in the fluorite. Microscopic study of the wall-rock gneisses shows the presence of planes of secondary inclusions with persistent strike crossing intergranular boundaries, such as have been described by Tuttle (1949). It is possible, therefore, that those secondary inclusions present in the dike minerals are part of a regional pattern and not peculiar to the dikes. If so, no pressure can be assigned to them here and no value of temperature calculated.

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DEEP TECTONICS AND ISOSTASY[1]

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ABSTRACT

A satisfactory geological interpretation of many gravity anomalies based on Airy's hypothesis of a floating crust seems impossible. The author therefore postulates a plastic deformation of a much thicker layer, in alternate anticlinal and synclinal undations, separated by surfaces dipping at approximately 45°. Such deformation, by the displacement of surfaces of equal density, causes gravity anomalies and disturbances of isostatic equilibrium. Examples are given, showing that the gravity anomalies observed in various regions (Hawaiian Islands, Mid-Atlantic Ridge, the Alps, the Mediterranean Basin) correspond in a satisfactory manner with those required by the hypothesis of plastic deformation.

The usual methods of calculation of the isostatic anomalies of certain regions indicate a large isostatic unbalance for which there is no adequate geological interpretation. The author's hypothesis shows that these same regions are in isostatic equilibrium. Although vertical adjustments tend to restore the isostatic equilibrium, there still remain pressure differentials which cannot be entirely suppressed by these vertical adjustments. They produce deep currents, the effect of which is to modify the previous isostatic equilibrium and, consequently, to provoke downward and upward movements in the mountain chains, as well as in the basins. The final result is a tendency to restore a stable equilibrium, in which the equal-density surfaces coincide with the equipotential surfaces, as before the deformation.

INTRODUCTION

Deep tectonics is here defined as deformation occurring from the surface to a depth of about 100 km. and, exceptionally, even deeper. The reality of tectonics at such depths is clearly shown by many researches. The author himself has several notes (1948*a*, *b*, *c*, *d*) on the subject, the object of which was to make a satisfactory interpretation of local problems of geology and gravimetry.

The author's studies led to a reconsideration of certain geological aspects of isostasy. This paper is therefore devoted to the isostatic equilibrium of the main structural units and its relation to deep tectonics. It is shown that the proposed method of interpretation indicates isostatic equilibrium in certain structures for which the usual methods of calculation yield large isostatic anomalies that have no geological explanation.

DEFINITION OF "ISOSTASY"

The word "isostasy" was first introduced to geology in an address delivered by C. E. Dutton (1889) at the Philosophical Society of Washington. Dutton said: "For this condition of equilibrium of figure to which gravitation tends to reduce a planetary body, irrespective whether it be homogeneous or not, I propose the name 'isostasy.' . . ." But this term expresses a thesis implied in the observations of J. H. Pratt (1855), who noted that the attraction of mountainous masses, notably the Himalayas, was less than that calculated. G. B. Airy (1855) suggested a physical explanation of the phenomenon, imagining a light crust sustained by a dense magma, "like a raft on water." This interpretation has so far been favored by a great many geologists and has stimulated the development of new hypotheses, such as those concerning the existence of the roots of mountains or the Wegener theory of continental drift.

However, this explanation did not convince Pratt; shortly afterward he (1859) proposed a new hypothesis, not very clear, of which he later (1871) gave a more precise statement: "Mountains must have been created by dilatation,

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depressions by contraction so that the amount of matter in any vertical column drawn from the surface to a level surface below the crust is now and ever has been approximately the same in every part of the earth." In this sentence is implicitly included the definition of compensation level. According to Pratt's hypothesis, as it is now understood, we may imagine the crust as made of prisms of different densities and variable heights, lying on a surface of compensation. The geologist may think this view somewhat oversimplified and physically remote from modern tectonic concepts; but, if Pratt's opinion is still debated and quoted in all classical works, it is because of the use which has been made of it by geodesists and more particularly by the United States Coast and Geodetic Survey.

Hayford (1909, 1910), Bowie (1912, 1917, 1924, and 1927), and Hayford and Bowie (1912), in a series of classical studies, have measured the values of g and deduced the isostatic anomalies, that is, the differences between the observed value and the normal value, corrected for influences of altitude, relief, and compensatory masses. The essential result of these studies has been to demonstrate that all the inequalities of relief in the United States are practically compensated isostatically and that the most likely depth of such compensation is approximately 100 km. I shall not stress the detail of calculation or the refinements which have been developed subsequently in order to take into account either the convergence of verticals or the so-called "indirect effect."

Yet it is quite obvious that Pratt's hypothesis, which to the geodesist is only a model for calculation as much justified as any other, is inadequate for the geologist, who desires a satisfactory explanation of the deformation of the earth's crust. So, more recently, Airy's hypothesis has been revived for the calculation of isostatic anomalies, particularly by the Finnish school, and results obtained in various regions of Europe have shown that the more important relief features are more or less exactly compensated (Heiskanen, 1924, 1938). Either method would assume that elementary prisms effectively compensated must have a minimum horizontal diameter, but, curiously enough, Bowie has shown that anomalies tend to increase with the diameter of the prisms. Vening-Meinesz (1923–1948, 1939) imagined in Airy's hypothesis a system of regional compensation caused by the bending of an elastic crust under the superficial overload, the effect being to distribute the compensatory masses in a more regional way. His tables provide for calculation according to the various hypotheses of regionality.

The discovery by Vening-Meinesz (1923–1948) and by Hess (1938*a*, *b*) of huge marine anomalies, contrasting notably with the isostatic balance, admittedly not perfect but at least approximate, observed in Europe and in the United States, requires a full revision of the hypotheses of deep tectonics.

The negative anomalies of the East Indies and of the Antillean and northwestern Pacific are so well known that an extended description of them is omitted. The coincidence of deep oceanic troughs and huge negative anomalies, expressed either as Bouguer or as isostatic anomalies, removes any possible doubt as to the existence of a deficiency of mass at depth. They are adequately explained by a synclinal fold, as set forth by Vening-Meinesz.

Positive anomalies are a more difficult problem. H. P. Coster (1945), reviewing the measurements of French and Italian expeditions in the western Mediterra-

nean Sea (Cassinis, De Pisa, and Dore, 1934; Cassinis and De Pisa, 1935; Pelissier, 1939), has pointed out very clearly that the hypothesis which reduces isostatic anomalies to a minimum corresponds to the degree of regionality, $R = 0$, whereas, with regionalities $R = 116.2$ or $R = 232.4$, bigger and bigger anomalies appear, becoming, for example, +60 to +120 or even +140 milligals. With the most plausible explanation, Mediterranean troughs still exhibit anomalies ranging from about +60 to +80. Likewise, in the East Indies, the Banda Sea shows positive anomalies of +90, whereas they exceed +150 west of Celebes.

The interpretation of these positive anomalies under Airy's hypothesis is very difficult, as I have previously shown (1948*a*). With density differences of 0.2, roughly corresponding to the differences between acid rocks, density about 2.8, and a basaltic substratum of density approximately 3.0, an infinite plate producing an anomaly of 84 milligals would be 10 km. thick and nearly double that thickness for 150 milligals. A cylinder, of which the axis was at a depth of 20 km., would attain a diameter of 28 km. in the first case and 40 km. in the second, and yet would not represent the lateral spreading of the anomalies under observation. If we assume the axis to be at a depth of 40 km., we find diameters of 40 and 54 km., respectively, which implies a thickness of the granitic crust exceeding 60 km.

These examples show that we are led to postulate the total or nearly total replacement of the granitic crust by extremely large basic intrusions, several tens of kilometers high and hundreds of kilometers wide, the existence of which does not seem very likely and has never been established in the much-eroded platforms. Moreover, by this interpretation, the crust would not have regained its state of balance, notwithstanding the enormous masses and overload on it; it seems still less probable, especially in the Mediterranean area, that the bordering mountains are actually compensated. Indeed, we know important intrusive masses, such as those in the Ivrea zone in the Alps, the French Pyrenees (De Cizancourt, 1948*d*), or the Betic Cordillera (southern Spain), but they are quite localized and their structural position is different from that which has to be postulated in Mediterranean Sea basins.

In addition, these masses, when once included in the crust, cannot move out of it, and there are no such bodies known in the outcropping Variscan ranges, either in Europe or in the United States or elsewhere. Thus we may conclude with some reason that such an interpretation of the anomalies, required by Airy's hypothesis, is not satisfactory to the geologist. What, then, is the true significance of the isostatic anomalies which are the differences between the observed values of g and a theoretical value calculated according to an assumed distribution of mass? The result obviously depends on the distribution postulated. Presented in this way, the problem is quite different from that which interests geodesists. Nevertheless, using the very arbitrary process of calculation based on a hypothesis more than a century old, they have demonstrated that, statistically, isostasy is confirmed by observation, and we can believe, therefore, that the crust as a whole is probably in equilibrium, except in some very limited regions.

On the other hand, isostasy does not imply a physical condition deduced in an unequivocal way from measurements of g determined on the surface. Brilloin (1928) has already shown that "it is

theoretically impossible to infer from purely geodesic data, as full as we may assume them, an answer to this question: 'Is the equilibrium of the crust absolutely, approximately, or not at all isostatic?'" Therefore, it will be sufficient to change the basic hypothesis in order to produce an appearance of equilibrium where other methods suggest an anomaly; but a basic hypothesis cannot be applicable only to a special case—it must apply to the problem as a whole.

FUNDAMENTAL HYPOTHESES OF DEEP DEFORMATION

The difficulty of obtaining a satisfactory structural interpretation based on Airy's hypothesis of a floating crust has led to a search for other solutions of this problem, particularly that of a plastic deformation reaching to a greater depth than those which have hitherto been used.

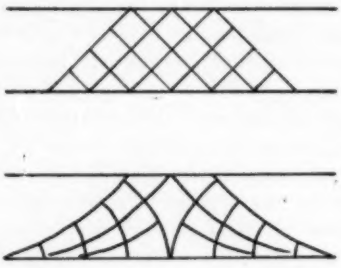

FIG. 1

Such a hypothesis requires the existence of a system of stresses. Orogenic hypotheses based on convective currents, although they may explain certain "cellular" structural patterns, are in themselves insufficient to explain the linear mountain chains. Linear formations can be produced by convection only, in combination with a velocity shear caused by exterior stresses. These stresses may originate either from the contraction or extension of the outer layers of the earth or from drag due to deep currents, convective or not, or from any other combination.

Stresses applied to plastic layers can bring about a great number of gliding surfaces, and in this case the deformation will be either a mass thickening or the formation of undulations (Kuenen, 1936; Kuenen and De Sitter, 1938). Surfaces of maximum shear, corresponding approximately to gliding surfaces, form, in the case of a layer resting without friction on its base, a system of orthogonal planes oriented at 45° from the main stresses, which are here horizontal. If, on the contrary, the deformed layer adheres to its base, surfaces of maximum shear, emerging at 45° at the surface of the earth, will be, respectively, tangent and orthogonal at the base, but the general outlook of the deformation will be altered very little (fig. 1).

Moreover, it is probable that both types are idealizations; the variation of physical properties with depth and the presence of plastic zones recently shown by Mintrop (1949) suggest intermediary solutions as the most probable.

These gliding surfaces, dipping at 45° between the undulations, or the zones of flexure which replace them will be the first to appear in the process of deformation; for they correspond to the regions where deformation is most rapid and where, consequently, relaxation will be least effective. The mass will then be deformed initially as a rigid medium, and only later will the plastic flow be established.

In a very clear manner Goguel (1943) demonstrated that the work necessary for further deformation of a given structure increases progressively up to the moment when the beginning of another

structure requires less energy than the continued deformation of the first one. The initial structure will be somehow solidified and incorporated in the nonplastified material, while a new structure will rise, and so forth. The beginning of a synclinal deformation will be followed automatically by a tendency to anticlinal deformation in one or both of the two immediately adjacent zones, owing to the necessity for the crust to equilibrate the momentum of buckling. A series of undulations formed in this manner would be practically limited to a level near the surface of the earth, because any elevation above the surface absorbs more energy than the down-warping of a fold below the surface.

The final result of this type of deformation will be a synclinal undulation, perhaps flanked by parallel undulations alternately anticlinal and synclinal, while in the deformed zones plastification will be revealed by the formation of a network of orthogonal surfaces of maximum shear. These synclinal and anticlinal undulations are present in an initial stage of deformation, for, as will be seen further on, tectonic evolution transforms the former into mountain chains and the latter into marine basins. In these undulations the deformation will be evidenced by currents of matter with a vertical component directed upward in the anticlinal undulations and downward in the synclinal undulations. Therefore, in order to avoid confusion, the major tectonic units corresponding to synclinal and anticlinal undulations are hereby designated as negative and positive "undations" (fig. 2). In a hypothesis slightly different from this, P. P. Bijlaard (1936) has shown that plastic deformation needs less energy than buckling.

As the final result of the deformation described above, currents of matter are set up, converging near the surface toward the negative undation and at depth near the center of the positive undation. A certain analogy with convection cells is apparent, thus leading to the belief that the deformation of undations may even play a trigger role in a system of convection currents because it causes a steeper temperature gradient. However, the density gradients will offset the effect of temperature, and one can expect that convection currents will be more or less quickly stopped.

FIG. 2

It can then be easily ascertained that the dimensions of the undations and those of the convections cells are sufficiently comparable to permit superimposition of both phenomena. In convection cells (Wasiutynski, 1946) of height h and dimensions λ and μ, the formula

$$\lambda = \frac{2}{b} \cdot h$$

holds, if one of the dimensions, μ, becomes infinite, with

$$\frac{1}{b} = 0.9$$

for fluids, and Jeffrey's second condition; and for viscous fluids (Rayleigh conditions):

$$\lambda = 2\sqrt{2}h .$$

The comparison will then be established in the hypothesis where the gliding surfaces are planes dipping at 45° with

$$\lambda = 2h ,$$

as is readily seen in figure 2, where the distance between the axes of the two un-

dations corresponds to $\lambda/2$, and, in the equally schematic hypothesis of a homogeneous layer, the gliding surfaces of which are tangent and perpendicular, respectively, to the base,

$$\lambda = 4.2h ,$$

approximately. In the intermediary hypotheses, λ will be included between these two extremes:

$$2h < \lambda > 4.2h .$$

Actually, experience shows that the interpretation of factual examples frequently gives the following results:

$$2.8h < \lambda > 3.6h ,$$

values which are intermediate between the figures given above and which are comparable in order of magnitude with the ones found for infinitely elongated convective cells.

It appears, therefore, that deformations of tectonic origin, within the limits of the deformed layers, can give rise to convection currents which will act in the same direction and that it will be difficult to distinguish practically between the consequences of these phenomena.

This is important, for it eventually provides an explanation of certain superficial mechanisms, such as the shortening of mountain chains measured on the basis of the length of the developed folds. Actually, the volume of mountain chains corresponds to a very small shortening, of the order of magnitude of less than a few kilometers, but the superficial flows can give more important relative displacements. It is even possible that a part of the structure considered due to gravity tectonics is due, in reality, to currents of convective or semiconvective origin. Moreover, the compressions and stretchings during isostatic upheaval, as will be shown below, can exaggerate considerably the apparent width of the folds developed. In the Alps, for example, the shortening calculated from folds is of the order of 300 km., whereas the shortening calculated from the author's undation hypothesis is only a few kilometers.

Consequently, it can be understood that plastic deformation shows a certain analogy with the effects of convection currents (Pekeris, 1936; Vening-Meinesz, 1947; Wasiutynski, 1946), if not in the mechanism, at least in the result. It then becomes very difficult to discriminate between the two types of structures because the former also gives rise to shearing effects, which will be at a maximum along dipping surfaces (Vening-Meinesz, Umbgrove, and Kuenen, 1923–1948; Vening-Meinesz, 1948). Nevertheless, the currents postulated by Vening-Meinesz are rising below the strip of negative anomalies, whereas we postulate, as does Griggs (1939), currents of an opposite direction.

The existence of surfaces dipping at approximately 45° is confirmed by the study of deep-focus earthquakes (Coulomb, 1945). These surfaces are here interpreted as zones of shearing that bound positive and negative undations (Cizancourt, 1948*a*). Many seismic foci are located at great depths, even as much as 700 km. Crustal deformation therefore extends to depths as great as one-tenth the earth's radius. But for reasons based on gravimetry, deformation below 100–120 km. in many places, especially the Alpine belt, seems to be very much reduced, as I have previously shown (1948*a*, *d*). It is worth while to note that Mintrop (1949), for seismological reasons, admits the presence of a plastic layer at a depth of 118 km. So, curiously enough, the crustal depth obtained by methods quite independent of the calculation of isostatic anomalies is neverthe-

less of the same order of magnitude as that required by Pratt's hypothesis.

From these considerations it may be concluded that, although the concept of a crust composed of independent vertical prisms is unjustified, we may consider it plastically deformed along surfaces of maximum shear, dipping at 45° and curving in depth. It remains to be seen whether this hypothesis is compatible with the data of gravimetry.

On the one hand, we have already noted that it is always possible to find a disposition of internal masses corresponding to the values of a given gravity potential observed on the surface and, on the other hand, that we may always imagine a disposition fitting both this observed potential and the isostatic condition. In other words, the problem is impossible of any mathematical solution and can be resolved only by accepting a fundamental hypothesis governing the distribution of mass in depth, which is not based on gravimetric measurements.

The disposition of disturbing masses will be entirely defined by (1) the shape of undations and (2) the density variation between the deformed and the undeformed sectors. The distribution of densities in terms of depth in the undeformed sector does not intervene. It is to be noted that either Pratt's or Airy's hypothesis, and some more recent ones, are also fundamental hypotheses but differ from ours.

Generally and intuitively favorable to Airy's hypothesis, geologists in many cases imagine a series of layers separated by level surfaces. The density of the layers would vary suddenly from one layer to the next. On the other hand, physicists generally postulate a law of density variation (Gutenberg *et al.*, 1939) compatible with ellipticity, moments of inertia of the earth, and seismological data. At present, the best solutions seem to be those of Bullen (in Gutenberg *et al.*, 1939; Handbook of physical constants, 1942). Goguel (1943) has recently given some continuous and discontinuous laws, the first approximating to the law of Legendre. In the following, as in my previous works, I have preferred to accept a continuous law, which presents some advantages of exposition.

Daly (1940) has based his depth interpretations upon a discontinuous law, the consequences of which are considerable. Postulating a substratum of crystallized basalt under a light sialic crust, he is led by his density hypothesis to have the former lying on a vitreous basalt of lower density. The intervening layer of crystalline basalt would therefore be mechanically unstable, and we would expect deep tectonic disturbances in the form of convection cells conditioned by the disposition of densities; the final effect would be successive meltings and recrystallizations leading to a magmatic evolution tending to restore the equilibrium. Recent laboratory measurements, however, do not seem to favor this hypothesis (Birch and Bancroft, 1942). Possibly, surface features of the moon constitute an example of this type of evolution, having been solidified by faster cooling.

The absolute value of density does not enter into the problem discussed here, and its variation in the course of tectonic deformation alone is considered. So, partly for reasons of simple convenience and partly to avoid the complications of Daly's interpretation, I have used, in problems previously studied (1948*a*, *d*), linear laws which, for a limit of 100-km. depth, approach Bullen's hypothesis. Concerning density variation resulting from deformation, the following remarks may be made:

The effect of deformation will be to lift or to lower surfaces of equal density and, consequently, to substitute at a certain depth h for a density δ, a density

$$\delta' = \delta [1 + f(h)],$$

$f(h)$ being a function of depth determined by the mechanism of deformation (fig. 3).

If we knew exactly the initial depth distribution of densities and the type of deformation, the calculation of the gravity anomalies would be easy. In the calculation the assumption was made that the change of density caused by deformation is proportional to depth. This assumption is appropriate where the density before deformation and the vertical component of the velocity are linear functions of depth. This relation holds for the velocity except near the edges of the undations in the postulated type of deformation. The first assumption means only that the tangent is used instead of the density curves between the surface and the base of the deformed layer and is not used for a linear increase of density outside the deformed layer. As shown in the following examples, the thickness of the deformed layer amounts, at the most, to 1.5–4 per cent of the radius of the earth, so that this assumption seems to be acceptable.

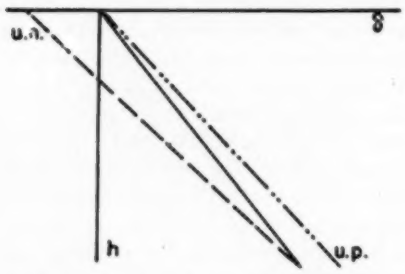

FIG. 3.—*Solid line:* density before deformation; *dashed line:* density in the negative undation; *dot-and-dash line:* density in the positive undation.

Moreover, the seismological results especially led to the acceptance of large discontinuities between a very limited number of different layers, but the velocity cannot be directly translated in terms of density, and, also, recent work (Mintrop, 1949) shows a greater number of distinct layers. It can be supposed that layers with large differences in composition and consequently in density have less chance of being stable, for any change of temperature induces magmatic segregation, which results in density sorting.

METHOD OF INTERPRETATION

From a physical point of view it is impossible to deduce the shape of disturbing masses from a given gravity anomaly; on the other hand, a physically possible mass distribution may be either impossible or unsatisfactory geologically.

In the following section an attempt has been made to compare interpretations based on two types of hypotheses—one of a floating crust and the other of a plastic deformation, as defined above. For this purpose Bouguer anomaly-type curves which can be easily compared with observed anomaly curves were established, in hypotheses of infinitely elongate structures. This comparison permits a conclusion concerning the depth and width of the disturbing masses under a given hypothesis. It is interesting to compare (1) an undation as defined above; (2) a compensatory mass concentrated in a strip of constant thickness, as in the Airy hypothesis; and (3) a compensatory mass concentrated in a strip of triangular section. This last assumption corresponds very nearly to Vening-Meinesz' hypothesis of the bending of an elastic crust.

The comparison of type and observed curves is made very easy and rapid by the use of the following contrivance. The type curves are calculated for a 100-milligal perturbation and with an arbitrary scale of distance $1/\lambda_0$. The observed curve is adjusted so that its maximum reaches 100 milligals by multiplying its ordinate by p. Then it is drawn with a scale of distance $1/\lambda$, so that it coincides with one of the type curves. It is noted that the latter corresponds to a depth d and to a width l. Therefore, the observed anomaly can be caused by a disposition similar to the one used for the type curves, but whose dimensions would be

$$\frac{\lambda}{\lambda_0} \cdot d, \qquad \frac{\lambda}{\lambda_0} \cdot l .$$

In practice the change of scale can be obtained automatically by drawing both the type and the observed curves on logarithmic or semilogarithmic paper and superposing one on the other. The multiplying factor to be used in order to obtain the coincidence of the observed and type curves can then be read directly. If δ_0 is the density factor characterizing the type curves, the corresponding density factor δ for the observed curves will be found by

$$\delta = \delta_0 \cdot \frac{\lambda_0}{\lambda} \cdot \frac{1}{p} .$$

This rapid procedure permits ready comparison of observed curves with any desired type of curves.

EXAMPLES OF INTERPRETATION

I will present here a few of the most characteristic examples, without pretending to give a complete geological interpretation of each case.

HAWAIIAN ISLANDS

The numerical data for this example are taken from Vening-Meinesz, Umbgrove, and Kuenen (1923–1948), recalculated as a modified Bouguer anomaly, using either the density of granite or that of basalt for the topographic correction, the latter being appropriate for a structure situated in the mid-Pacific.

This example is especially interesting because the Bouguer anomaly appears practically isolated and, after subtraction of an obviously linear regional anomaly, a symmetrical curve (fig. 4) can be drawn. Figure 5 illustrates how a satisfactory coincidence is obtained with a

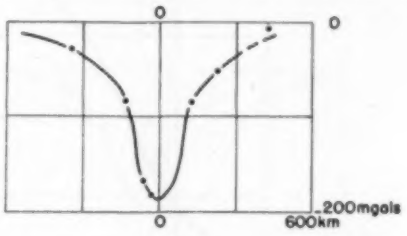

FIG. 4

type curve corresponding to a negative undation 60 km. wide at the surface and 100 km. deep, with

$$\frac{\lambda}{\lambda_0} = 2.3 .$$

The width and the depth can be deduced as

$$d = 100 \times 2.3 = 230 \text{ km.},$$

$$l = 60 \times 2.3 = 138 \text{ km.}$$

Comparison with the diagram of compensatory masses concentrated in a strip with rectangular section shows that no one coincidence is satisfactory. With a strip of triangular section, similar to the one considered by Vening-Meinesz, the observed curve occupies an intermediary position between two curves, one at

31-km. depth and with a width of 310 km., and the other at 90-km. depth and with a width of 230 km. However, no very satisfactory coincidence is obtained. It will be noted that Vening-Meinesz, using isostatic anomalies, considers a probable compensation with R between 170 and 240 km., that is, an average width of 400 km., corresponding well enough with the median part of the negative undation. But it can be seen that this kind of compensation, even taken at 0-km. depth, gives a Bouguer anomaly quite different from the observed one. The assumption of a negative undation is therefore not incompatible with the observed anomaly and gives a better result than compensatory masses in the hypothesis of a floating crust.

It will also be noted that the width of 140 km. for the undation at the surface corresponds almost exactly to the width of the submarine plateau bearing the Hawaiian Islands. This topographic high, therefore, should be interpreted as the superficial expression of a large negative undation and not as due to the accumulation of volcanic rocks, as has been done.

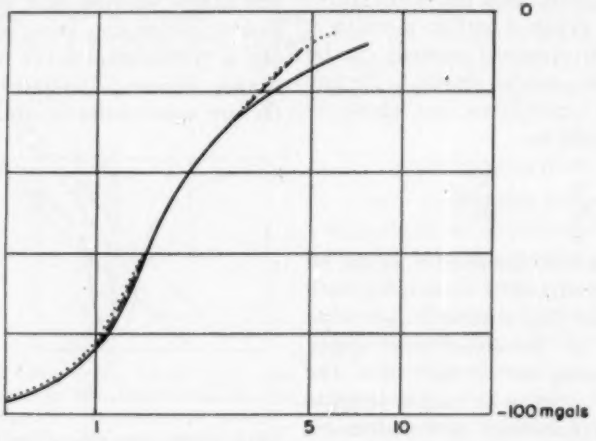

FIG. 5.—Hawaiian Islands, type and observed curves on semilogarithmic co-ordinates (arbitrary scale of distances). *Dotted curve:* calculated type curve; *solid and dashed lines:* north and south branches, respectively, of observed anomaly.

PYRENEES AND ALPS

The discussion of these regions will be brief because I have recently (1948*d*) published an interpretation of the first one. I was able to show that the Bouguer anomaly in the Pyrenees can be split in two, one part corresponding to a negative undation and the other to a positive anomaly due to a basic intrusion at shallow depth. It is found that the negative undation of the Pyrenees would be 40–50 km. in width at the surface and at a depth of about 100 km.; a depth of 80–100 km. was originally admitted (De Cizancourt, 1948*d*), based on a slightly different curve.

In the Alps, where the Bouguer anomaly is of the same type as that of the Pyrenees, more careful interpretation is necessary, owing to the added effect of neighboring anomalies and to their winding paths, which render a cylindrical approximation less justified. However, a

good coincidence of the observed curve with that of a negative undation, 100–110 km. wide at the surface and at a depth of 140–150 km., is found. This width covers the whole of the zone of nappes from the Aar massif to the Dinarides.

In the compensation hypothesis of Vening-Meinesz, there is also an acceptable coincidence with a strip 110 km. wide, to a depth of 22 km. It will be noted that the width of 110 km. represents that of the high mountain belt, and the compensation, therefore, would be a purely local one. The assumed depth is consistent with that of the granitic layer.

MID-ATLANTIC RIDGE

A last brief, but very instructive, example is Vening-Meinesz' profile over the Romanche deep between Brazil and occidental Africa. Here, as in the Hawaiian Islands, we are dealing with a Bouguer residual anomaly obtained by subtracting a very regular and practically linear regional anomaly from the observed curve. The interpretation of the residual anomaly may easily lead to a symmetrical minimum with two superimposed maxima (fig. 6). Although other interpretations are possible, particularly that of several minima, this one seems to be consistent with what is known of other profiles across the Mid-Atlantic Ridge.

A negative anomaly is thus obtained, the coincidence of which with an anomaly curve of a negative undation is excellent (fig. 7). We find that this undation has to be 350–400 km. wide and 280–300 km. deep in order to represent the observed curve. Because the Mid-Atlantic Ridge in this region is 400 km. wide, we would then have an enormous undation, more reminiscent of those observed in all continental massifs than in the folded mountain chains. Moreover, the sharpness of both positive anomalies must be due to concentration of heavy masses at depths of a few tenths of a kilometer at the most. The striking analogy with positive anomalies in the Alps, Pyrenees, and the Betic Cordillera (southern Spain) tempts one to attribute them to a comparable cause, namely, intrusive basic rocks. This interpretation seems, curiously enough, to be confirmed by the presence of dunite outcrops at

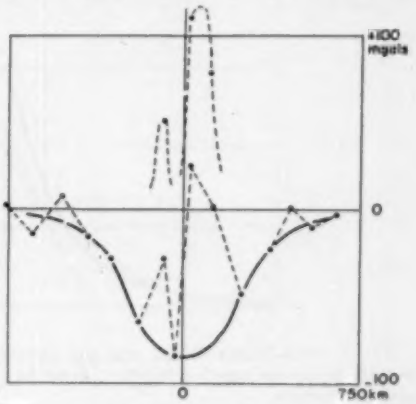

FIG. 6.—Mid-Atlantic Ridge. *Dashed line and observed points:* residual Bouguer anomaly; *solid line:* anomaly due to a negative undation, after subtracting the two positive maxima (plotted in the positive field of the diagram).

St. Paul Rocks, which are located on the crest of the Mid-Atlantic Ridge about 11° west of the Romanche deep (Tilley, 1947).

This example does not claim to give a precise interpretation because of the small number of measured points, but it shows the advantage of the use of Bouguer's anomaly and the possible comparisons with the better-known conditions in the Alps and Pyrenees. Invoking a compensation below a floating crust gives a depth of compensation of the order of magnitude of 70–100 km., which is more or less meaningless geologically.

WESTERN MEDITERRANEAN SEA

A Mediterranean anomaly running parallel to and north of the coast of French North Africa and south of the Balearic Isles may be used as an example of a positive anomaly. This Bouguer anomaly reaches about 200 milligals at its maximum on a line between Ibiza and Algier, and its width at a level of half-maximum is about 160 km. (fig. 8).

The compensatory mass, 160 km. in width, centered on this maximum and taken at 20-km. depth, should have a thickness of about 30 km., with a density difference of 0.2. This would mean the replacement of the granitic layer by a rock of approximate basalt density, exceeding its own thickness. But, in reality, this solution is not a satisfactory one because it gives an anomaly curve differing from the observed one, and it would be necessary to put the compensatory mass down to 70 km. in order to get an acceptable coincidence. With a more carefully shaped mass, one can consider it at a shallower depth, but it is still necessary to postulate thicknesses varying from 10 to 30 km., having a density contrast varying from 0.5 to 0.2. I do not insist on the detail, but it

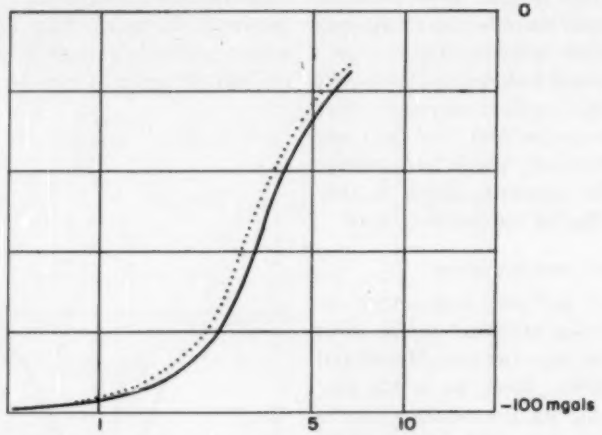

FIG. 7.—Mid-Atlantic Ridge, type and observed curves on semilogarithmic co-ordinates. *Solid line:* anomaly due to the negative undation; *dotted line:* one of the two calculated curves between which the observed curve runs.

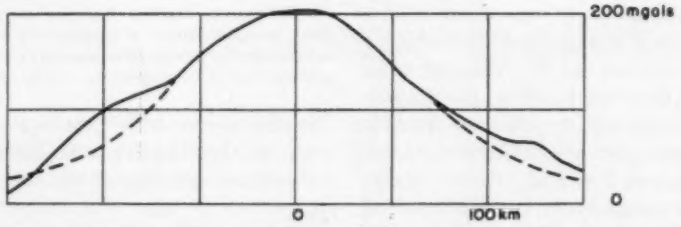

FIG. 8.—Western Mediterranean, observed Bouger anomaly. *Dotted line:* residual curve after subtracting local effects.

can readily be seen that the difficulty is always the same, and it is necessary to replace the granitic layer totally, or almost totally, by basic rocks in order to get an anomaly comparable to that observed. A geologist can hardly understand the mechanism of such a generalized intrusion because nothing comparable is known where outcrops are visible, especially in the outcrops of basement rocks on the coast of North Africa. However, one can suppose that a less uniform distribution of the heavy masses may bring them very easily up to the surface.

On the other hand, the solution of a positive undation does not raise any difficulties of interpretation. The observed Bouguer anomaly then coincides in a satisfactory manner with a positive undation 200 km. wide and 100 km. deep (fig. 9), a depth of the order of magnitude of those obtained in the Alps and Pyrenees. This result is worth nothing because it would be difficult to conceive the mechanism of adjacent positive and negative undations reaching to very different thicknesses.

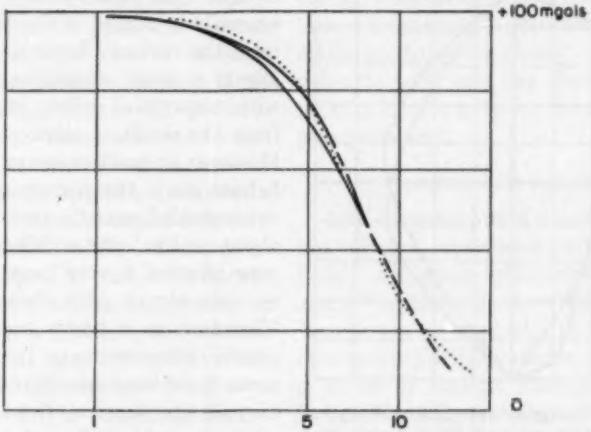

FIG. 9.—Western Mediterranean, type and observed curves on semilogarithmic co-ordinates. *Solid line:* observed anomaly (with two curves corresponding to the north and south branches of the anomaly); *dotted line:* calculated curve.

TOPOGRAPHIC RELIEF AND DEEP DEFORMATIONS

The result of deformation, according to the preceding fundamental hypothesis, will be, finally, a transferring of masses from negative to positive undations and a variation of the mass of each of them, negative for the former, positive for the latter.

The undeformed zones being assumed to be in equilibrium, the deformed elements will no longer be in equilibrium, and, under the Archimedean thrust, they will tend to shift, some of them upward, the others downward, to a degree easy to calculate when we know the density contrasts deduced from comparison with type curves. Of course, this mass displacement will not be effected without provoking superficial tectonic accidents, the details of which are not important here. It is simple, then, to calculate the volume of rock which counterbalances the vertical forces, i.e., the relief—positive or negative—produced by the isostatic adjustment of tectonic units. An example of this type of calculation is in

the literature (De Cizancourt, 1948*a*, *d*). Comparison with existing relief immediately shows whether or not they are in equilibrium, and the isostatic anomaly can be determined by the difference between the average height calculated and the average height observed.

Naturally, it is no longer possible, as in Pratt's hypothesis, to balance individual vertical prisms, even if each block corresponds to a positive or negative undation, separated by surfaces dipping at 45°, because each of these blocks will exert a pressure upon its neighbors and, consequently, will upset the isostatic adjustment of the whole set. The disadvantage of this method is that it is not possible to establish a characteristic value of the isostatic anomaly at each point because an average can be determined only for a whole structural complex, the value being determined from the combination of geological and gravimetric data.

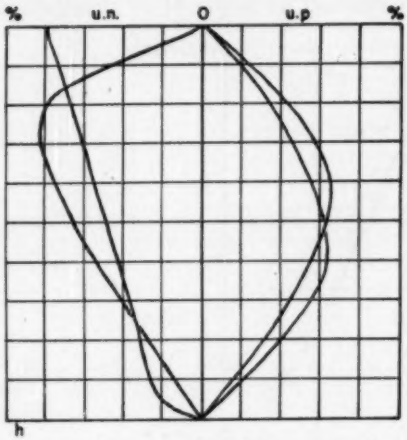

FIG. 10.—Percentage of the Bouguer anomaly due to slices 10 km thick; *u.n.*: negative undation; *u.p.*: positive undation. The two curves on each side correspond to two different points, one on the maximum (or minimum), one on the side.

As shown in the preceding examples, the results obtained are in some cases in conformity with those of classical methods but in some cases are very different. It is easy to see that the conformity is quite satisfactory for negative undations corresponding to mountain chains but very bad for positive undations which correspond to marine basins. If we calculate the influence of successive horizontal slices of equal thickness on the total anomaly, curves of the type shown in figure 10 are obtained, and it can easily be seen that 50 per cent of the negative anomaly is located in the first 15–30 km. from the surface. Because this anomaly affects a zone coinciding substantially with superficial relief, it differs little from the result of classical calculations. However, in positive zones, where things behave as if the disturbing mass were concentrated near the core of the fold at about 50 km., the width of the surface zone affected is very large, and there is no coincidence with classical methods. Therefore, it is easily seen how gravimetric measurements in mountainous zones have been considered as confirmation of the classical views of geologists who accept Airy's hypothesis or its variants. Application of the same methods to positive anomalies of the marine area of Alpine folding has led to considerable and systematic anomalies (Coster, 1945), whereas calculations according to the above process almost eliminate these anomalies.

Although a discussion of isostasy in the western Mediterranean would lead us into too much detail, an example may be given to show that the methods of compensation of Airy or Vening-Meinesz give isostatic anomalies of the order of magnitude of 50–100 milligals, which are minima for a degree of regionality $R = 0$. Conversely, the hypothesis of a positive undation gives, with the existing topog-

raphy, a difference in altitude operating below 200 meters in the case of an individual compensation of the positive undation and a little over 200 meters for the adjacent negative undations, the masses involved by the lack of compensation being approximately equal for positive and negative undations. Thus we arrive at the following idea of distribution of pressure in the depths, such that the surplus mass of the positive undation causes a hydrostatic pressure which counterbalances the excess topography of the negative undation. We can now understand why positive isostatic anomalies in the western Mediterranean appear as minima, with a degree of regionality $R = 0$. These are due to the fact that the compensatory masses in positive undations, contrary to those in negative undations, are concentrated in a narrower width than that of the undations on the surface, so that, truly speaking, the degree of regionality should be less than zero. It is therefore understandable that in this case the positive isostatic anomalies are smaller with $R = 0$ than with $R > 0$. The preceding discussion shows how isostatic anomalies are closely dependent on the methods of calculation and may not be real but are only the result of comparison between the hypothesis used in their calculation and facts resulting from observation.

Isostatic anomalies are not, however, devoid of any meaning. The classical methods yield concordant results in the continental areas where the crust is practically in equilibrium. Indeed, the contrary state would have been unlikely, especially if we grant that tectonic phenomena affect a thickness of at least 100 km. Major structural elements, therefore, actually have noteworthy differences of masses. Consequently, the argument can be reversed, and we can say that, because the equilibrium of the crust is statistically demonstrated for a very large part of the earth, it probably exists elsewhere and therefore that the method of calculation which gives the lowest average departure from isostasy is statistically more likely than others, unless geologically valid reasons demand another conclusion.

Although calculation alone does not explain gravimetric measurements, such calculations combined with some fundamental concept lead us to the most probable explanation compatible with isostatic conditions. Isostasy is therefore a valuable tool, enabling the geologist to make a choice between several possible interpretations.

BASINS AND RANGES

True orogenic zones are commonly, if not always, associated with concomitantly deformed adjoining continental areas. The Germano-type folds in Alpine Europe are an example. In Europe, the Hercynian-Variscan chains peter out in a series of massifs (Brittany, French Massif Central, Ardennes, Vosges, etc.) and of basins (Parisian, Hanovrian Basins, etc.), the outlines of which follow neither Alpine nor Hercynian-Variscan trends. The general aspect of the geological map is that of a checker pattern. The geological history of these basins and mountains reveals a sequence of positive and negative vertical movements not obviously related to horizontal compression induced by the main tectonic paroxysms of the mountain ranges. Were this the case, these repercussions should have occurred only during the uplift of the Alpine chains. They are much more easily explained as movements similar to those within the orogenic belt, but with a much lower intensity.

If we take into consideration "cellu-

lar" basins, likening them to convection cells, we find that their dimensions should be greater than the width of mountain chains. With a quadrangular shape, $\lambda = \mu$, we have

$\lambda = 4h$ (Rayleigh, viscous fluids);

$\lambda = 2\sqrt{\frac{2}{b}} \cdot h = 3.1h$ (Jeffrey).

It is

$$3.1h < \lambda < 4h .$$

In the Alpine area we have found

$$100 \text{ km.} < h < 140 \text{ km.}$$

Therefore, we should get convection cells with dimensions

$$310 \text{ km.} < \lambda < 560 \text{ km.},$$

averaging 450 km. in width, dimensions which can be compared favorably with the dimensions of European, African, or American basins (for example, the Paris Basin, 400 km. in diameter). It is very likely, however, that we do not have here, strictly speaking, a simple convection regime and that deformation of tectonic origin plays the same role here, too, as in linear chains; but perhaps this role is less evident.

Therefore, it seems possible to account for the oscillations of basins and massifs by a deep deformation, expressed not in elongated anticlines and synclines but in a system of domes and basins. We can imagine that the progressive damping of stresses will not permit the building of linear ranges but that it will break the foreland into structures, cellular in form, in which the flow is alternately upward and downward, recalling, somewhat, Bénard's convection experiments (see Wasiutynski, 1946).

ISOSTATIC EVOLUTION

Our initial hypothesis, postulating an increase of density with depth by whatever law, allows stable equilibrium to be achieved. But this equilibrium can be upset either by application of orogenic pressure or by convection currents or, more likely, by a combination of both. Deformation will continue as long as the currents are not entirely checked by penetration through zones of decreasing density, as pointed out by Daly (1940). After deformation, equal-density surfaces no longer coincide with equipotential surfaces. Observation seems to show, however, that the material is rigid enough to allow block movement, by which isostatic adjustment of the undations is achieved.

But, if we consider the material as viscous, whatever may be the present distribution of materials, a new equilibrium will definitely be reached only when a disposition of densities coinciding with equipotential surfaces is once more established. Temporarily different dispositions might persist, and the high viscosity would permit the building-up of superposed masses behaving as solids; but ultimately another arrangement will necessarily follow, the same masses being actually constituted of a viscous material. According to Pratt's hypothesis, it is clear that pressures are not balanced on both sides of the dividing surfaces between vertical prisms. Isostasy according to Pratt implies, therefore, the existence of solid columns separated by surfaces which are practically frictionless. The same remark applies to isostasy after Airy. Consequently, the state of isostatic compensation of relief can be considered as only temporary.

Now let us consider, on the basis of the author's hypothesis outlined above, the trend toward equilibrium from the time when a folded system is completed. There will be, first, a tendency to subsidence "en bloc" of the positive undation and to a lifting-up "en masse" of the negative undation until the balance of

pressure is achieved. Actually, however, the former will undergo a shallower subsidence, and the latter will rise higher, any lateral displacement being excluded. In fact, let us consider hydrostatic pressures. The density δ, being a linear function of depth h, is

$$\delta = \delta_0 + Kh ,$$

the pressure p will vary from dp when the depth varies from dh, and it follows that

$$dp = \delta dh$$
$$= (\delta_0 + Kh)\, dh ,$$
$$p = \int_0^h (\delta_0 + Kh)\, dh = \delta_0 h + \tfrac{1}{2} Kh^2 .$$

The pressure will thus follow a parabolic law and will grow rapidly with

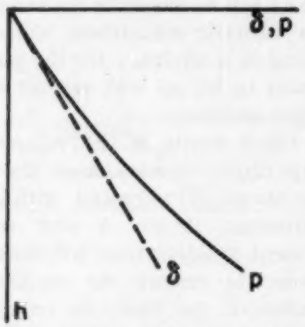

FIG. 11.—Density and pressure as functions of depth.

depth. (Strictly, it would be necessary to take into account the increase of g with depth, but it is small, less than 1 per cent at 200-km. depth, and can be disregarded [fig. 11].)

The vertical stress exerted by one mass upon another, each of them being assumed sufficiently rigid, will be on the dividing surface

$$E = \int_0^h p \cos \theta \, ds ,$$

$ds \cos \theta$ being the projection of an element ds of the dividing surface on a horizontal plane (fig. 12).

We can write, for the unit of length $\Delta y = 1$,

$$ds \cos \theta = dx ,$$

and, if the equation of the dividing surface is, on the section plane $y = 0$,

$$x = \varphi (h)$$

$$E = \int_0^h f (h)\, \varphi' (h)\, dh .$$

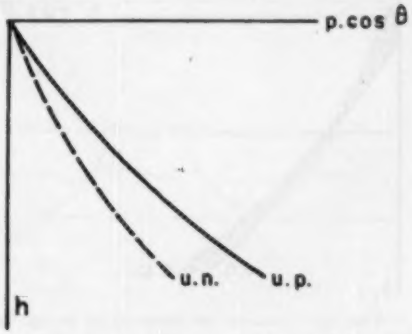

FIG. 12.—Archimedean pressure, as function of depth in positive and negative undation, before isostatic adjustment.

If E_P and E_N are the two functions corresponding, respectively, to positive and negative undations, the difference

$$E_P - E_N$$

represents the Archimedean thrust. It will be canceled for a given position, namely, that in which the areas of curvilinear triangles included between the two curves (fig. 13), corresponding, respectively, to positive and negative undations, are equal. (In the case of undation blocks limited by planes, $\cos \theta$ takes a constant value and the curves in p and $p \cos \theta$ differ only by a constant term.) In this position, pressure differences will be balanced and the movement will slow down in such a way that we shall assume that there is equilibrium; mountainous zones will present a slightly negative isostatic anomaly, and sea de-

pressions a slightly positive anomaly. This is actually observed, the former in the Mediterranean and the latter in the East Indies.

Yet this equilibrium is unstable, inasmuch as there are still differential stresses between the different undations. A steady equilibrium would arise only by cancellation of these stresses, that is, if

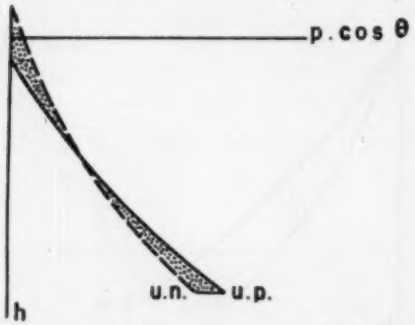

FIG. 13.—Archimedean pressure, as in fig. 12, after isostatic adjustment.

the two $p \cos \theta$ curves come to coincide. Besides, the difference between the curves in p will always imply a term in h, so a vertical displacement of the masses alone, one with respect to the other, cannot bring the two curves into coincidence. We have:

$$\delta = \delta_0 + f(h) ,$$

$$p = \delta_0 h + \int f(h)\, dh ,$$

$$\Delta p = (\delta_{0P} - \delta_{0N})\, h + \int f_P(h)\, dh - \int f_N(h)\, dh ,$$

the letters P and N referring to positive and negative undations, respectively.

The Δp will equal zero at any depth only if the coefficients of $f_P(h)$ and $f_N(h)$ are identical and if the δ_0 is the same. In all the other cases a differential pressure will remain which could not be canceled by a vertical translation. Under these conditions, a stable equilibrium could not be permanent, and the isostatic equilibrium will leave stresses persisting. They will, however, tend to vanish in course of time because of a viscous flow which will go from negative to positive undation in the upper part and from positive to negative undation in the lower part. In the upper level there will be a tendency to overlapping: the mountain ranges will override the foreland and disturb it. In depth, on the other hand, the positive undation core will collapse. Finally, the flow will produce a homogeneous distribution of densities. Then pressure curves will be altered in such a way that they will attain greater values in the negative undation as well as smaller values in the positive undation. The areas of the curvilinear triangles of figure 13 will no longer be the same, and a new isostatic adjustment will occur, resulting in a tendency for the positive undation to lift up with respect to the negative undation.

In other words, if the volume and average density do not change, the shape of the blocks will vary and, with it, the Archimedean thrust. A new vertical movement of adjustment will then arise in order to restore the equilibrium. Therefore, it can easily be understood that, in course of time, there will be a subsidence of mountains and a lifting-up of sea troughs. This is clearly illustrated in the Hercynian-Variscan chain, in which we see today the almost total disappearance of gravimetric anomalies which formerly were a feature of this chain, as they are of the present Alpine chain. In short, independently of any deformation of an orogenic nature, chains born of negative undations will undergo complex oscillations, with successive upward and downward movements. Erosion, too, will alter equilibria by mass transferences toward basins, and this will impede the ideal equilibrium.

Therefore, the whole tectonic evolution may be summarized as follows (fig. 14): (1) Orogenic evolution will start with a very marked lack of balance and a considerable anomaly. (2) The result of adjustment en bloc will be the uplift of chains born of negative undations with all tectonic complexities caused by the flow of material through a narrow belt, thereby resulting in intense stretching, folding, and overthrusting toward the foreland; simultaneously, basins will subside. (3) Differential pressure at depth will provoke a deep viscous flow; negative and positive undations will be deformed, altering Archimedean thrusts and resulting in reverse movements tending to establish the equilibrium again. (4) This, however, will cause a new lack of pressure balance, and a new displacement will arise. (5) The result of these successive movements will be the progressive disappearance of relief, together with gravimetric anomalies, the condition existing prior to distortion tending to reappear. Present-day chains show all

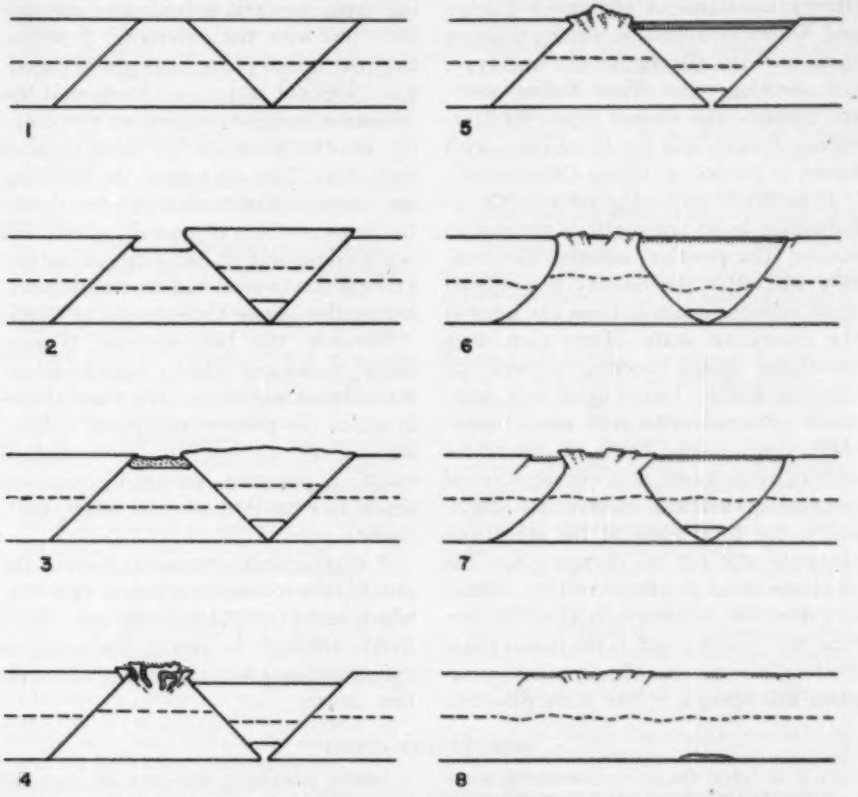

FIG. 14.—Tectonic evolution of negative and positive undations. *1*, formation of shear surfaces; *2*, folding in positive and negative undations; *3*, erosion and sedimentation; *4*, isostatic adjustment and folding of the mountain belt; *5*, erosion and sedimentation; *6*, deformation by deep flow; *7*, isostatic readjustment; *8*, final stage of equilibrium.

these evolutionary stages, namely, ranges in formation (East Indies, northwestern Pacific); compensated chains coming to maturity (Alps, Rocky Mountains); chains more or less destroyed by the double action of deep flows and erosions (Hercynian-Variscan chains of Europe and America). Likewise, among positive zones we may distinguish the first type, still showing relief (East Indies, western Pacific), the second type (Mediterranean Basin), and the third type, with basins in process of lifting (Maracaibo).

It would be surprising indeed if things happened in so schematic a manner in reality. The positive undation deformation will alter the density by causing some vitreous zones to cross the limit of the crystalline state. Here, then, is a modifying factor working toward increasing density. In the same way, magmatic differentiation will occur, especially close to the limits of crystalline and vitreous zones, as a consequence of alternating vertical movements. Obviously, the total mass of the structural elements will not be changed, but the distribution of densities will be altered in a direction tending to oppose the vertical movement which is the initial cause of the phenomenon. Finally, these processes will operate in the same direction as viscous flows of the late orogenic phase.

In the case of cellular basins and massifs that lie outside the chains, the isostatic evolution will be similar to the evolution of linear chains of the corresponding type: isostatic subsidences and uplifts; but with the difference, it seems, that the initial phase of isostatic unbalance does not appear so clearly and the evolution remains progressive and deep. On the other hand, the last phase remains very clear. This appears in the uplifting and emptying of basins and the downthrow of portions of massifs, which will occur commonly in the form of narrow grabens due to tensional stresses, remembering the classic experiments of Cloos.

Between the two extreme types—linear chains and cellular basins—all intermediates may occur. There are chains in which the geosynclinal phase is lacking on the surface but, nevertheless, where a negative undation exists in depth, like the Pyrenees (De Cizancourt, 1948*d*).

A diagrammatic representation of the structural evolution is given in figure 14, which must be taken only as a very rough attempt to sketch the complex events noticeable in the history of mountain chains.

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GEOLOGICAL NOTES

A HYDROTHERMAL KAOLINITE DEPOSIT IN WEST TEXAS[1]

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INTRODUCTION

The existence of several clay deposits near Fort Davis and Marfa, Texas, has been known since 1917, when efforts to use clay from these deposits were first made (Vogel, 1942). During the course of routine work on the evaluation of these clays as ceramic raw materials, thin sections of the clay-bearing rock were made at the Research Laboratory in Ceramics of the University of Texas. Examination of the thin sections to determine beneficiation possibilities disclosed several interesting mineralogical features bearing on the origin and alteration of the deposits. The following paragraphs present microphotographs and discussion of these observations.

LOCATION

The deposit from which the samples were taken for this investigation is called the "Medley deposit," from its location on the D. O. Medley ranch. With regard to the original land surveys in the district, the Medley deposit lies about midway along the south line of section 6 in the East Line and Red River Railroad Company Survey, Block WJG 3. The deposit lies about 1 mile north of the road from Fort Davis to Valentine and about 17 miles by road west of Fort Davis, in Jeff Davis County, Texas.

GEOLOGY

The Medley deposit lies on the southern margin of the Davis Mountains. The structural geology of this district has been discussed by C. L. Baker (1934, pp. 162–163) and by C. L. Baker and W. F. Bowman (1917). The major structural feature is a broad down-warp, near the center of which there is a granite intrusive. This igneous intrusion has caused the formation of local anticlinal structure by doming the overlying rocks. Among the overlying rocks are Cretaceous sediments which are overlain, in turn, by a complex series of volcanic tuffs, breccias, and lavas. The lavas are rhyolitic or trachytic porphyries. They have been assigned to the Tertiary geologic period by F. B. Plummer (1932).

The Medley deposit lies near the southwestern edge of the igneous intrusive in the upturned and beveled edges of the interbedded lavas and tuffs (Baker, 1934, pp. 287–288). Alteration of the volcanic rocks and deposition of the clay were presumably caused by emanations from the igneous intrusive rock.

METHOD OF INVESTIGATION

A compass survey of the deposit for sample location is shown in figure 1. The topography relative to an arbitrary zero of elevation is also shown along with the tentative boundaries of silicified and kaolinized zones. All samples are designated by the number of the pit from which they were taken.

The X-ray spectrometer was used to make quantitative mineralogical analyses of a number of composite samples, as well as of samples specially selected because of obvious differences in appearance. The method used for mineralogical analysis in this laboratory differs in some details from the methods described in the literature (Carl, 1947), but the variations are not of sufficient application to the present subject to be discussed here.

Chemical analyses were made of the com-

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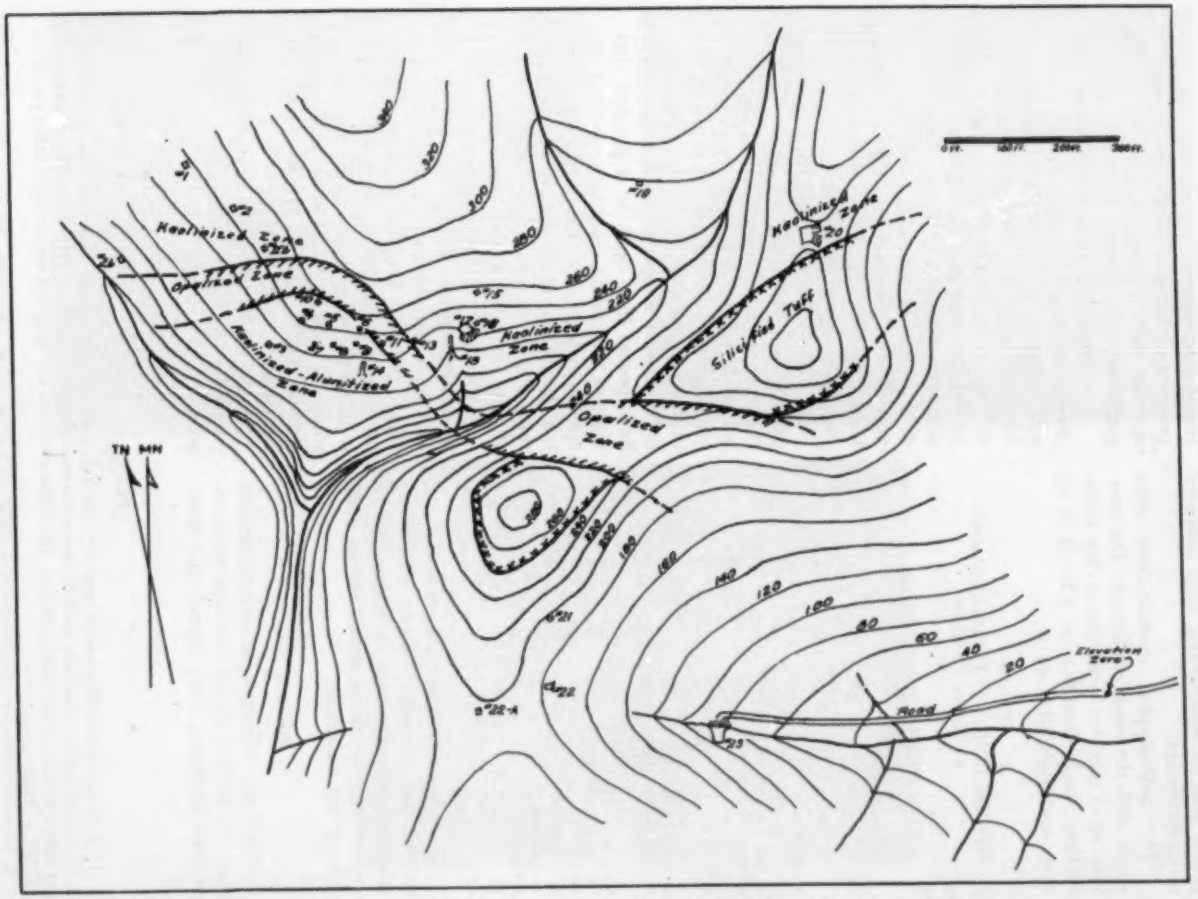

FIG. 1.—Compass survey of the Medley deposit, showing sample locations and outcrops of rock types

posite samples representing large tonnages of kaolinitic ore.

The petrographic examinations were made with the usual equipment. The presence of at least two varieties of clay in the sections made identification difficult in all cases and doubtful in many.

TABLE 1
MINERAL CONTENT OF MEDLEY SAMPLES BY X-RAY ANALYSIS

SAMPLE FROM PIT	PER CENT			
	Kaolinite	Cristobalite	Quartz	Alunite
1—pink ore	28	52	20	Tr.
1—white ore	53	37	6	4
2—hard white ore	51	37	4	8
2—soft white ore	87	9	4	0
2*b*	65	23	8	4
II*b*	28	58	4	10
3	31	49	7	13
4, 5, 6—composite	26	57	9	8
7, 8, 9—composite	25	39	6	30
11	25	69	6	0
13	63	31	9	0
15, 16, 17—composite	69	15	12	4
20	80	10	6	4
21—pink ore	0	79	0	21
21—white ore	23	56	Tr.	21
22*A*	0	60	40	0
23	56	12	30	2

Thermal analysis methods were not used because the complexity of the mineral assemblage indicated that interpretation of the differential curves would be not only difficult but dangerous.

MINERALOGY

The X-ray diffraction patterns of samples from the Medley deposit revealed the presence of kaolinite, both alpha- and beta-cristobalite, quartz, and alunite. The proportions of these minerals in the various samples vary widely, as is shown in the quantitative analyses of table 1.

The reflections from kaolinite are predominant enough to mask the presence of any halloysite in the samples. The reflection from halloysite that sometimes occurs for a spacing of 10 Ångstrom units was not observed, although the writer does not consider this to be conclusive evidence of the absence of halloysite, because this reflection may be very diffuse. Therefore, although there may be halloysite in any of the samples, it is not the major clay mineral in any of them.

The cristobalite pattern arises from the presence of opaline material and possibly from the presence of some crystalline cristobalite (Levin and Ott, 1933). No crystalline cristobalite could be identified under the microscope, even though the cristobalite reflections were sharper than would ordinarily be expected from opal. It is possible that some of the quartz reflections are from the opaline material also (Levin and Ott, 1933), but the amount of quartz visible in the sections is sufficient to account for most, if not all, the intensity of the quartz reflections.

With regard to the actual quantities of the minerals shown in table 1, it is of interest to compare the X-ray analyses with the actual chemical analyses of the composite samples. In making this comparison the opal is taken as being substantially pure silica, while the alunite is taken as pure potash alunite. Table 2 shows the results of the comparison.

On the whole, the agreement between the values for silica and alumina is reasonably good.

PLATE 1

A, Kaolinite (*K*) replacement in opal (*O*). The first generation of kaolinite has been altered to alunite ($K+A_1$), whereas later kaolinite partially altered to alunite ($K+A_2$) and partially unaltered (*K*) forms veins and replacements in the first generation. The white areas are still later and are probably halloysite (*H*?). Pit. No. 1. Analyzer out, 61×.

B, Zoned alunite (*A*) rhombohedra in kaolinite (*K*). Opal (*O*) on lower edge. Pit No. 1. Analyzer out, 278X.

C, Kaolinite (*K*) replacing quartz in altered porphyritic lava. Groundmass is opal (*O*). Pit No. 20. Analyzer out, 16X.

Alunite, kaolinite, and opal relationships

Solution tubules and sponge quartz crystals

DESCRIPTION OF THIN SECTIONS

Plate 1, *C*, shows how the quartz phenocrysts in a sample from pit no. 20 are replaced by kaolinite. It should also be noted that there are fracture veinlets leading to the replaced phenocrysts. In other places in the section this fracturing becomes intense, and the kaolinite is found as vein filling bounded by sharp matching walls and containing sharp fragments of the walls. Microfaults in the flow structure may be seen, and many fragments have been floated from their original positions.

In plate 1, *A* and *B*, the relation of alunite to the kaolinite and opal in a sample from pit no. 1 is shown. In plate 1, *A*, the lower left and upper right corners are opal. A wide vein of kaolinite containing two generations both of clay and of alunite passes through the opal. The walls of the veinlet show some replacement. The dark delta-shaped area occupying most of the field to the upper left is fine-grained alunite embedded in kaolinite. This latter material has been fractured; the small fracture veins and the area to the lower right are filled with a second generation of clay, which is, in turn, impregnated with a second generation of alunite. The writer believes that the second generation of clay mineral may be halloysite because the birefringence and index of refraction are somewhat lower than in the first generation.

It is of interest to note that the tiny veinlet of clay bounding the lower left-hand area of opal is deposited in such a way that the slow ray vibrates perpendicularly to the walls of the veinlet, i.e., the cleavage is perpendicular to the walls of the vein.

Plate 1, *B*, from the same section as plate 1, *A*, shows the two generations of alunite in a more positive way. Here the alunite is in rhombohedral crystals, showing two zones of growth. The matrix in which the alunite lies is kaolinite, and the writer believes that the alunite crystallized after this particular kaolinite veinlet formed. The dark material at the lower edge is opal.

Plate 2, *A*, shows a very unusual structure, which might be mistaken for perlitic structure were it not for observations made during the preparation of the slide. The two round areas in this picture are cross sections of tubules that are presumed to have served as passages for gases or solutions in the rock. Numerous occurrences of this kind were found. The tubules shown in the picture extended all the way through a rock slice about ¼ inch thick before the slice was sawed for the section. The tubule in the upper right is filled with opal, except for a small core of chalcedony. The tubule in the lower left has a zone of spongy quartz surrounding the chalcedony.

Plate 2, *B*, shows a similar tubular structure developed in the more highly kaolinized area of pit no. 20. The light-colored areas are kaolinite mixed with a little quartz. The

TABLE 2

COMPARISON OF X-RAY ANALYSES WITH CHEMICAL ANALYSES*

Sample from Pit	Per Cent SiO_2		Per Cent Al_2O_3	
	Chem.	X-ray	Chem.	X-ray
2*b*.....	63.60	61.2	27.53	27.2
3.....	70.30	70.4	19.06	17.0
4, 5, 6.....	85.31	77.2	9.66	13.3
7, 8, 9.....	64.00	56.0	19.03	21.0
15, 16, 17...	62.12	59.1	27.18	28.7
20.....	58.85	53.2	30.16	33.1
23.....	69.55	69.0	22.99	22.9

* Analyses by D. A. Schofield, Research Laboratory in Ceramics, University of Texas.

PLATE 2

A, Cross section of solution passages in opal (*O*). Central areas are chalcedony (*Ch*), which in the lower left tubule is surrounded by spongy quartz. From about 150 feet north of pit No. 1, fig. 1. Analyzer out, 61×.

B, Kaolinite (*K*) replacement in solution passage similar to that shown in *A*. Also shows breccia vein filling to lower right. Dark areas are opal (*O*). Pit No. 20. Analyzer out, 61×.

C, Sponge quartz (*Q*) crystals in opal. Dark areas are opal (*O*). Pit No. 22*A*. Analyzer in, 61×.

deposition of kaolinite has been at least partly controlled by the tubular structure. Replacement and vein filling by kaolinite are both in evidence in this section.

Spongy quartz is highly developed in an opaline matrix which gives the X-ray pattern of both alpha- and beta-cristobalite. The opal forms the main portion of the rock. As seen in the field, this white rock appears to be an altered porphyry. It contains numerous small vugs, some of which appear to be negative crystals of quartz. The vugs on weathered surfaces are partially filled with montmorillonite, as determined by X-ray diffraction.

In thin section, as shown in plate 2, *C*, the opal is isotropic and homogeneous, in so far as residual structure of any other kind of rock is concerned. The quartz sponges are optically continuous and are best described by stating that they are formed as if a very large number of tiny rectangular parallelepipeds about $15 \times 15 \times 30\ \mu$ had been suspended in a liquid at a uniform distance of 20–50 μ from one another and the quartz had then crystallized in the leftover space. The positions occupied by the hypothetical parallelepipeds are now filled with opal, which is continuous with the matrix. The spongy crystals of quartz range up to 1 mm. in diameter, and some of the crystals are isolated, while others have grown until they interfered with one another. In relatively few cases the spongy quartz is continuous with solid quartz crystals, and many of the solid crystals show cracks, interpreted here as contraction cracks.

The opal contains a few inclusions of brown, nearly opaque material thought to be limonite or a basic sulphate of iron. The latter is likely because identifiable copiapite was found in some of the breccia sections. The opal also contains numerous crystals of zircon, about $4 \times 20\ \mu$ in size. Some of the crystals are geniculated twins.

The most highly silicified rock associated with the deposit is the silicified tuff described by Baker (1934) and not pictured here. It occurs in large masses around and within the deposit. The tuffaceous structure is easily seen in the thin sections. The material of the rock is fine-grained quartz, with some chalcedony lining and filling openings.

DISCUSSION

Field evidence and the examination of the sections show plainly that silicification was the most widespread and active influence during alteration of the original volcanics. The potash, soda, and alumina of the volcanic material have been almost entirely removed by the altering solutions. Iron must have been relatively less soluble in these solutions, since it has remained in much of the altered rock as a stain which clearly depicts the structure of the original rock. Such details as small lath-shaped crystals of feldspar may now be seen as clear, opalized areas in a groundmass of heavily iron-stained opal. Moreover, the vein filling accomplished at a later stage in the history of these solutions is uniformly white and low in iron. Quartz, opal, and chalcedony were formed by the silicification process. The spongy quartz was probably formed by devitrification of the opal, as has been suggested by Fenner (1936, p. 249). It may well be, since the opal shows the X-ray patterns of both alpha- and beta-cristobalite, that regions consisting of one of these types of opal are devitrifying, while the other type remains unchanged and fills the interstices of the quartz sponges.

The highly brecciated zones in which the kaolinite is found doubtless served as conduits for hot springs because evidence of the passage of solutions is found in the sections. As the temperature and pressure decreased, the same solutions that had silicified deeper zones began to drop their acquired load of alumina by replacement and precipitation in already silicified rock.

The possibility of a strictly hydrothermal origin for kaolinite does not enjoy great popularity at present. Davison (1928) has claimed such an origin for some of the English china clays in Cornwall; but Ross and Kerr (1930) have disputed this theory quite sharply. The writer believes that the evidence presented here shows that the kaolin-

ite in the Medley deposit received its alumina at the expense of the surrounding silicified areas and that the process was one of hydrothermal deposition and replacement.

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FROST-THRUSTING IN THE NORTHWEST TERRITORIES[1]

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INTRODUCTION

During the summers of 1947 and 1948 the writer carried out geologic mapping of two areas, one north and one southeast of Indin Lake, N.W.T., Canada, between Great Bear Lake and Great Slave Lake (fig. 1). The following account is largely descriptive and is based mainly on observations in the area north of Indin Lake.

The Indin Lake area is underlain by volcanics and metasediments of the Yellowknife group, intruded by late pre-Cambrian granite and allied rocks. The originally sedimentary rocks now consist of quartz-mica schist, phyllite, impure quartzite, and slate. They are dominantly schistose. The volcanics have been altered but are not so schistose as are the rocks of sedimentary origin. The beds and flows are vertical or nearly so. The granites and allied rocks are blocky, massive types, locally gneissic. Bedrock is well exposed, and large areas are covered only by a thin veneer of glacial debris and scattered boulders. Eskers, sand plains, and morainic material provide a deeper cover locally. Hills and ridges rise abruptly 100 feet, or locally as much as 450 feet, above adjacent lakes and muskeg swamps.

[1] Manuscript received February 27, 1950.

The summer season is short, and maximum temperatures rarely exceed 85° F. Spring breakup normally occurs about the middle of June, freezeup in October, while snow flurries are not uncommon during the latter part of August. In winter, temperatures of −40° F. are attained almost every year, and a minimum of −72° F. has been recorded at Great Bear Lake. The 23° F. mean annual isotherm passes about 100 miles south of the area, as does the southern boundary of continuous permafrost (Jenness, 1949).

Since little has been written concerning this type of frost action on bare outcrops, the writer has found no terms descriptive of these particular phenomena. Consequently, the following terminology is used:

Frost-thrusting is used for the process whereby large blocks of rock have been raised, commonly vertically, or have changed position with respect to the rest of the outcrop, owing to the frost action.

Frost-thrust blocks refers to the blocks of rock which have been moved by frost-thrusting.

It seems that in the terminology suggested by Bryan (1946) "frost-thrusting" is included by the broader term "congeli-

turbation," and "frost-thrust block" is one kind of congelifract.

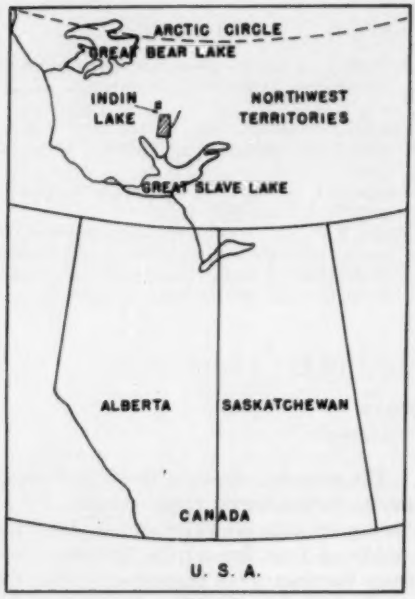


FIG. 1.—Index map showing location of the Indin Lake district.

DESCRIPTION OF FROST-THRUST BLOCKS

GENERAL DESCRIPTION

The sequence of breakup of bedrock by frost-thrusting is clearly shown in the area. Small cracks are visible where joints and planes of foliation have been widened. Where such breaks are present, one or more blocks of rock may be raised relative to the outcrop surface. In some cases the block is tilted or hinged along only one fracture, resulting in a sloping surface and a "frost-thrust scarp" across the outcrop.

After the blocks have been thrust upward a certain height, they begin to split along planes of weakness and to tilt sideways because of the lack of sufficient confining pressure. The final stage is marked either by an irregular pile of broken blocks or by a rim of broken material surrounding a deep depression or "crater." The crater is formed by the outward tilting and falling of the broken frost-thrust blocks. The centers of these craters are partly filled with water, ice, and broken rock, so that precise depth measurements could not be made. In one case the bottom could not be reached with a pole approximately 12 feet long. The dimensions of these craters vary, some being more than 25 feet across. The shape of most is elongate rather than circular.

The even and gradual upward movement of the frost-thrust blocks is shown by the presence of rounded glacial boulders perched on top of some of the blocks, several feet above adjacent bedrock. Some of these are so balanced that only a slight push is required to topple them from their perch. Many of the blocks are slightly wedge-shaped in cross section, narrowing downward (pl. 1, *C*). Measurements taken are not considered exact because some spalling probably has occurred. The dimensions of blocks thrust up from bare outcrops are the most reliable, for here there is no evidence of spalling. In any case, spalling of the frost-thrust block would tend to reduce, rather than to emphasize, the wedge form. Table 1 gives a few dimensions of three blocks to illustrate the wedge form.

PLATE 1

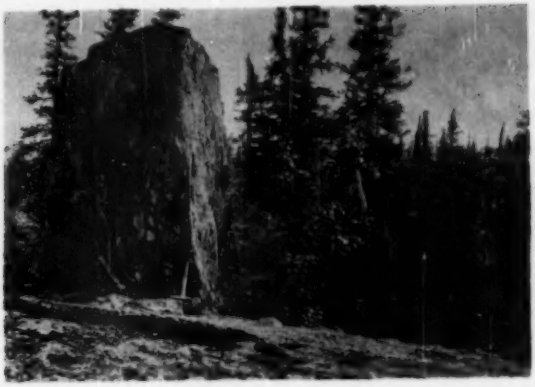
A, Pluglike frost-thrust block of basic volcanic. Note the small scarp in the left foreground.

B, Frost-thrust block, "hinged" at one end. Most hinged blocks have smaller dimensions than this example.

C, Part of a wedge-shaped frost-thrust block. The lower portion is tightly encased by the surrounding outcrop. Very little spalling has occurred.

D, Postlike frost-thrust block in knotted quartz-mica schist. The base of this joint is tightly encased by the surrounding rock.

E, Long, narrow frost-thrust block in quartz-mica schist.



A

D

B

E

C

Frost-thrust blocks

A notable feature of some of the wedge-shaped blocks is that the enclosing rock tightly encases the narrower basal portion along the sides. The upper parts show little or no cracking, so that originally the encasing outcrop edges must have been farther apart than they are at present.

A peculiar form observed resembles an oversized cement post projecting from the outcrop (pl. 1, *D*). Only three of these were seen, one in knotted schist and two in basic volcanics. They are 3–4 feet high and approximately 1 square foot in cross section. This form of frost-thrust block appears to be controlled by jointing.

CONTROL BY LITHOLOGY

The rock type affects the form and the degree of development of frost-thrust blocks. The best expression of forms and the largest number of frost-thrust blocks are in those areas underlain by metasediments, especially quartz-mica schist and phyllite. Long, narrow, slightly wedge-shaped frost-thrust blocks are typical, the long dimension being parallel to the schistosity (pl. 1, *E*). The early stage of frost-thrusting in the metasediments is characterized by numerous small, platy frost-thrust blocks and some larger ones, raised a few inches above the general rock surface. In some cases the frost-thrust blocks in schist are hinged at one end (pl. 1, *B*). The bottom of one fully exposed block of this type was flat because of a horizontal joint. The rock below the joint showed no evidence of movement.

Among the metamorphosed sedimentary rocks, frost-thrust blocks develop preferentially in the finer-grained types. Where beds show a distinct decrease in grain size toward the top, frost-thrusting may develop ragged "walls" on each side of the coarser-grained layers. Variations in the amount of upward movement and spalling of the blocks contribute to the ragged profile. This occurs where the change from coarse to fine grain in a bed is rather abrupt. Some excellent examples of this type of preferential frost-thrusting a few miles south of the map area were reported to the writer by M. L. Miller.

In granitic rocks and nonschistose volcanics frost action rarely produces the distinctive raised blocks described above (pl. 1, *A*). The common result is a mass of large, irregular joint blocks.

Diabase dikes in the area are vertical or nearly so, with polygonal joint blocks normal to the walls. These joint blocks are sometimes rolled or pivoted out of their original position. In one case a block of schist had moved up along the contact with a diabase dike.

CONTROL BY TOPOGRAPHY

Frost-thrust blocks are best developed in areas of low relief, where drainage is poor and bedrock well exposed. Just a few inches of cover will provide enough insulation to prevent frost-thrusting. Where little or no soil or other cover is present, the full effects of temperature changes can operate. Where more than a few inches of cover protect the bedrock, frost-thrust blocks are absent or rare.

TABLE 1

DIMENSIONS OF THREE WEDGE-SHAPED BLOCKS (IN FEET)

Length at Top	Length at Outcrop Surface	Average Width at Top	Average Width at Bottom	Height
7.7	7.4	1.6	1.4	3.2
5.7	5.4	1.4	1.3	3.5
4.5	.....	1.0	0.95	1.7

In flat areas blocks are thrust vertically upward and eventually break and tilt to form the craters or irregular piles of debris described above. On hillsides, however, there is a downslope movement. On the upper part of the hill near the shoulder numerous crevices are formed by downslope migration of blocks. In some cases the crevices are as much as 4 feet wide at the top, narrowing with depth. Ice and water usually occupy the deeper portions of the crevices. The loosened blocks generally are tilted downslope. As further breakup occurs, a low talus fan may be formed. Where less move-

ment takes place, the result is a mass of broken rock in approximately its original position.

PHYSICS OF FREEZING

Very little information is available regarding the action of freezing water on rocks. Most papers on frost action treat the effects on soils rather than on bedrock.

When water freezes, there is a volume expansion of 9.05 per cent, but the force developed by crystal growth is important also. Some investigators believe that ice-crystal growth provides the major force in frostwork. Taber (1929) suggests that pressure effects accompanying freezing in soils are due to the growth of ice crystals and that excessive heaving is due to segregation of water as it freezes. However, the segregation is obtained in clay sizes but not in coarser soil materials.

Frost-thrust blocks involve the upward movement of large rock units. The ice which provides the required pressure forms along joints, planes of schistosity, or any other available fractures. When water seeps into such a crack, it can start to freeze whenever the temperature is low enough. It may freeze at 0° C., but, as it expands, the pressure developed would lower the melting point, so that high pressure could not develop unless the water is entrapped.

Bridgman (1915) has shown that with increasing pressure the freezing point may drop to a minimum of about −22° C. Grawe (1936) points out that water has a marked tendency to cool below the freezing point before solidifying. The drop in temperature may be to −5° or −6° C. Crystallization may then progress so rapidly that time is insufficient for the escape of some water to compensate for the expansion. Under these conditions a strong pressure develops suddenly but can never exceed that which would cause the ice to melt. Smith-Johannsen (1949) notes that, normally, water will not freeze until it is cooled to about −20° C., except when in contact with ice.

Ice has a coefficient of expansion about ten times that of rock; hence, after crystallization, pressure may be relieved by a drop in temperature. This contraction tends to pull the ice away from the rock surface. The entrance of water or water vapor into this space could cause more ice to form, filling the crack. A rise in temperature would then cause the ice to expand, again exerting pressure on the rock.

FORMATION OF FROST-THRUST BLOCKS

The various stages of development of frost-thrust blocks indicate that the sequence of events is as follows:

Water enters along some plane of weakness in the rock, such as a joint or foliation plane, and crystallizes when appropriate temperature conditions are realized. The pressure developed by freezing or by later expansion of the ice acts against the adjacent rock. In a vertical crack the pressure is horizontal, and, if the rock is not free to move, the ice may melt, thus relieving the stress. Water entering along horizontal joints and freezing needs only to develop a pressure sufficient to exceed the forces due to friction and to the weight of the block involved, in order to thrust the block upward. Schistose rocks have many planes of weakness along which movement could occur with minimum friction. A fine-textured rock would provide less frictional resistance than would a coarse-textured rock.

Once a block has been thrust upward, it is prevented from settling back when the ice melts by three factors: (1) the frictional resistance of the adjacent rock, (2) the presence of debris which has fallen into the crack, and (3) the horizontal movement of the surrounding blocks. The space below the block will then be larger, and more water can accumulate during the next thaw and increase the amount of movement during the next freezing cycle.

FORMATION OF WEDGE-SHAPED BLOCKS

The exact significance of wedge-shaped blocks is not known. It may be that pressure, developed by the formation of ice

along planes of foliation or schistosity which are not parallel to the bedding planes, has a vertical or nearly vertical component sufficient to raise the wedge, a sort of "squeezing-out" process. Wedge-shaped blocks with the smaller, lower portion tightly encased by the adjacent rock may be due to movement of the encasing rock. This movement is no doubt related to forces developed along the fractures in other parts of the outcrop. Any water freezing below the block would add to the upward movement.

AGE OF FROST-THRUSTING

It is clear that the effects of frost-thrusting now exposed have developed since the area was last covered by glaciers. Many frost-thrust blocks project from outcrops which bear glacial striae, and some blocks themselves are striated on their upper surfaces. Some blocks have lifted glacial boulders high above the outcrop. Thus the earliest possible date of origin is known. Frost-thrusting is apparently going on at the present time, as indicated by the unstable position of some of the blocks, by the unfilled craters, and by the lack of any visible spalling on many of the angular blocks.

The amount of thrusting which has occurred can be averaged over postglacial time. The movement was probably slow in the early stages, but the gradual enlargement of openings would result in a faster rate of movement in the later stages. Climatic changes would affect the intensity of movement. As the ice retreated, the area at first would have been in the periglacial zone, the climate changing more or less gradually to that of the present. Hence the thrusting may have been of varying intensity in different parts of postglacial time.

ACKNOWLEDGMENTS.—The writer wishes to express his appreciation to Dr. Herbert E. Wright for many helpful suggestions and criticisms.

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THE ERRONEOUS USE OF *TJAELE* AS THE EQUIVALENT OF PERENNIALLY FROZEN GROUND[1]

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The strong international interest in the problems, both scientific and practical, of perennially frozen ground is encouraging both for the advance of science and for international co-operation. It is, however, imperative that the development of the science of cryopedology should not be hampered by the introduction of unsuitable terms or by the careless use of those that have been adopted.

One of the characteristics of the far north is the presence of perennially frozen ground. This phase is accurate in description and

[1] Manuscript received July 20, 1950.

[2] Deceased August 22, 1950.

correct in form (Taber, in Bryan, 1948) but long and awkward. Several attempts have been made to find a single word to express the same idea. During the war Muller (1945) introduced the etymological monstrosity "permafrost," and many European writers adopted the Swedish word *tjaele* or its Norwegian equivalent, *taele* or *tele*. This word, taken from the common speech of Sweden, was introduced by Bertil Högbom (1914)[3] as a substitute for the German *Eisboden*, which he says is easily confused with *Bodeneis; tjaele* designates not only frozen soil but also the condition of the ground. However, Högbom does not pretend that *tjaele* means either a permanent (in the human sense) or a perennial condition. In fact, he makes a clear distinction and, on pages 261, 263, and elsewhere, uses *perenne* and *perennierenden tjaele* when referring to perennially frozen ground.

Most writers assume that *tjaele* means perennially frozen ground (Schafer, 1949), but Dr. Ivar Skarlund, professor in the University of Alaska, assures me that this is an error. Most Scandinavians, outside of specialists, have never experienced perennially frozen ground, since it occurs only sporadically in the most northern part of the Scandinavian peninsula or in its high mountains (see data in Högbom, 1914). The word *tjaele* and its variants, however, are used throughout the peninsula. Dr. Skarlund says that one frequently hears farmers say, "We are going to plow as soon as 'tjaelen' goes out of the ground" or " 'Tjaelen' is deep this year." Thus the common meaning of the word is "frozen ground" without any implication as to the length of time involved.

Some authors seem to think that *tjaele* was originally a Lappish word, but in a recent letter Dr. Nils Hörner assures me that it is purely Scandinavian. Dr. Kenneth P. Oakley has suggested orally that, in sound, it is not far from the Latin *gelare*, "to freeze," and *gelu*, "frost," and may be a loan word. However, I have not been able to pursue the more remote etymology of the word. Apparently, there is no question that it means only "frozen ground."

Troll (1947) makes the same distinction as Högbom, speaking of *tägliche tjaele, jahrliche tjaele*, and *perenne tjaele*, for diurnally, annually, and perennially frozen ground. These uses are irreproachable from a linguistic standpoint. Troll believes that *gefrornis* is an adequate German substitute for *perenne tjaele*. But this German word is not quite suitable in sound for a borrowing into English and would be difficult to convert into a verb or an adjective.

The English and French advocates of *tjaele* (see discussion of Bryan, 1947) are, however, left on unsound ground in their championship of *tjaele* as a short single word for perennially frozen ground.

The writer again ventures to suggest "pergelisol" (from L. *per*, "through," *gel* from *gelare*, "to freeze," and *sol*, from *solum*, "ground"), a properly coined word. It is easily converted into any European tongue, and from it the verbal adjective "pergelated" can easily be made. Also, the important processes of the formation or building-up of perennially frozen ground, "pergelation," and of its destruction, "de-pergelation," can be expressed. The difficulty of making adjectives and verbs from *gefrornis, tjaele*, and "permafrost" is one of the handicaps of these terms.

As the growth of pergelisol in the periglacial region with every change of Pleistocene climate toward the cold is a logical and provable consequence, "pergelation" is a useful word. Similarly, changes of climate toward the warm resulted in the loss of frozen ground or "de-pergelation." The areal extent of pergelisol in the periglacial zone is one of the prime problems in modern studies of ancient frost-action. One can be

[3] I am surprised on rereading Högbom's monograph to find on p. 266 that he states (in translation): "By 'regelation' is meant repeated freezing and thawing. . . . Disruption by frost [*Spaltenfrost*] in hard rock is a generally known result of regelation. . . ." This term was first defined by Tyndall and Huxley (1857; see also Tyndall, 1896). Tyndall (1896, p. 382) gives full account and quotes Helmholtz: "This regelation occurs when two pieces of ice are simply pressed together." Fortunately, Högbom's unfortunate redefinition of "regelation" has not been followed by others, so far as I am aware.

certain on theoretical grounds that, to the south of the ice sheets, pergelisol had a limit at sea level and rose in altitude more or less parallel to the snow line. This is the subnival zone of Troll. It may, toward the subtropics, have been replaced by "etesigelisol," the *jahrliche tjaele* of Troll, and in the tropics by "diurnigelisol," or *tägliche tjaele* of Troll. "Etesigelisol" (from L. *etesia*, "season") and "diurnigelisol" (from L. *diurnus*, "daily") are simple extensions of the original pergelisol and may prove useful terms as the generalizations of Troll are pursued by the present large group of workers.

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REVIEW AND DISCUSSION[1]

Elements of Oil Reservoir Engineering. By SYLVAIN J. PIRSON. New York: McGraw-Hill Book Co., Inc., 1950. Pp. vii + 441; figs. 221; charts 3; tables 36. $6.50.

Approximately 55 per cent of geology graduates become petroleum geologists; thus the oil industry is the greatest employer of geologists. To a minor extent the young petroleum geologist does field mapping of the classical type. To a much larger extent he "sits on a well," observing the progress of its drilling, picking up formational "tops," and recommending where to test for a potential "pay." Finally, a small, but rapidly increasing, professional field is that of reservoir petrology, where the geologist comes into close contact with the production of oil, both flush and secondary, and the business of exploitation. Hence a petroleum geologist's job is essentially twofold: either to find a new field and locate a new oil well or help in the production of oil. Both these occupations are "oil-finding." In the field of oil exploration, to a very large extent, the classical anticlinal theory, originated by Sterry Hunt in 1861, practically applied by I. C. White in 1891, and adopted, after a fifty-year lag, by the more progressive oil companies between 1905 and 1910, still holds sway. Today, forty years later, a frenetic search for closed structures still goes on: iron-legged field geologists wear out shoe leather looking for reverse dips, while secretive geophysicists, assisted by innumerable mysterious (and expensive!) gadgets, search for the deformation of buried strata that have been infallibly pronounced as key horizons by pontifically disagreeing micropaleontologists. The success of this tried-and-true procedure can be seen from the fact that the number of dry holes necessary to discover a new oil field has increased in the last ten years from five to nine. In the meantime, a simpler and easier way to increase oil production, namely, to improve recovery methods, is still largely in the hands of physicists and engineers, who, regardless of their many other splendid qualifications, are as a group totally unfamiliar with the most important factor in their calculations, namely, the character and possible performance of the reservoir rock itself.

According to the recent survey of the American Association of Petroleum Geologists, the number of geology graduates in the spring of 1950 exceeds the number of conventional openings in the geological profession by approximately 3 to 1. It seems, therefore, that geologists, specifically petroleum geologists, would improve their value to the industry and make a few openings for themselves by entering the field of petroleum production as valuable and indispensable partners.

This may prove possible even in the exploration field, inasmuch as the work of the modern petroleum geologist consists mainly in the interpretation of results obtained by geophysical devices, particularly electric logs, which in essence are supposed to be instruments that probe the quality of a fluid reservoir. Interpretation of electric logs, as this reviewer has seen it, in addition to some very dubious ideas concerning the record of fluid-bearing strata, consists in matching "wrinkles" and "kicks" and similar attempts at correlation. This is essentially the same Murchisonian procedure as that followed in paleontology *by directly* matching guide fossils in different horizons. This primitive procedure produces too many failures because the geologist does not possess the faintest idea of what rock factors he is really considering.

The purpose of this discussion, however, is not to give a plug for sedimentary petrology but to bring to the attention of the geologic profession a worth-while book which should go a long way toward helping petroleum geologists in maintaining, consolidating, and expanding their present position in the oil business. *Elements of Oil Reservoir Engineering*, by Sylvain J. Pirson, is an entirely new type of text. Pirson is one of the few scientists who have inquisitive minds and a firm knowledge of several fields at once; he is a good reservoir engineer and an outstanding geophysicist (being the originator of one of the very few methods of geochemical prospecting that seem to work relatively well in a fair number of cases) and has, although not first-hand, a solid appreciation of the value of sedi-

[1] Manuscript received October 30, 1950.

mentology and respect for rocks as such. Out of 435 pages, the first 181 are devoted to the reservoir rock and to its study by physical methods, such as electric logs, capillary-pressure studies, porosity, permeability, etc. There is a 20-page adaptation of the Krynine classification of sediments as applied to oil fields, followed by Pirson's personal interpretation and classification of oil-field structures on a large scale, an invaluable description of traps that should be an eye-opener to many petroleum geologists. Finally, there are 150 pages on physical and chemical aspects as related to the geologic setting of the performance of reservoir rocks and of the instruments and methods which are used by geologists, geophysicists, and petroleum engineers to gauge such performance and make predictions either of an exploratory or of a production nature. The chapter on logs—electric, radioactive, and others—goes a long way away from the kind of uncritical material that is usually published about the subject. It attempts to give an interpretation of the basic factors, with emphasis on clay behavior and other mineralogical elements which enter into the production of these famous "kicks" that are so unscientifically accepted as gospel truth by the average geologist. This chapter alone should make it worth while for many practicing petroleum geologists to get the book. Besides the first 181 pages, which are of definite value to the exploration geologist, the book, from chapter iii on, is of great interest not only to the petroleum engineer but to any geologist who wants to make a place for himself by switching from the overcrowded (and not too successful!) field of petroleum exploration to the job of consultant on oil production.

Pirson's text consists of the following chapters: "The Microscopic Study of the Reservoir Rocks and Structures," "The Megascopic Study of the Reservoir Rocks and Structures" (a total of 181 pp.), followed by chapters on "Reservoir Fluids" (55 pp.), "Reservoir Force and Energies" (35 pp.), "Fundamental Equations of Reservoir Engineering" (21 pp.), "Fundamental Production Process" (80 pp.), and "An Analysis of Field Data" (50 pp.). The book is distinctly modern. It is far removed from the "practical" petroleum texts of the cookbook variety, dealing with drilling and pumping, and also from the misleading theorizing of purely physical and physicochemical studies of alleged reservoir performance by physicists and "petrophysicists" who operate with idealized porous media that do not exist in nature. The book forms a useful bridge in many respects between the petroleum engineer and the petroleum geologist.

Pirson's text points very much to the importance of sedimentary petrology both in finding and in producing oil. Since sedimentary petrology progresses by leaps and bounds, in some places Pirson's text deals with out-of-date sedimentological material, but this shortcoming does not detract from the fact that Pirson's book is the first to bring the important petrologic factors to the attention of both the geological and the engineering profession. It may be well for the petroleum geologist[2] to get away from the good old routine of 1928, when this reviewer was pushing a Brunton compass through the southern Mexican jungle looking for dip reversals (a procedure which is still industriously followed in 1950, although under somewhat more comfortable living conditions, since the field outcrops are replaced by "kicks" on electric logs), and to try to understand the famous dictum of Wallace Pratt: "Geologists have been so enamoured of anticlines that they have failed really to look for oil."[3] Many opportunities are present in this field, and the study of Pirson's text will be a valuable aid in this direction.

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[2] By "petroleum geologist" is meant a man well trained in physics, chemistry, mathematics, and petrology. The normal and typical college graduate in geology (even a Ph.D.!), indoctrinated with the heroic, Grand Canyon type geologic traditions of the 1830–1950 period, will not have much of a chance in this line of geologic endeavor.

[3] This is misquoted by Pirson, who attributes (incorrectly) the following, very similar version to Pratt (p. 78): "We have looked so much for structures that we have failed to look for oil."

REVIEWS

Geochemistry. By KALERVO RANKAMA and TH. G. SAHAMA. Chicago: University of Chicago Press, 1950. Pp. xvi+912; figs. 53; tables 221. $15.00.

This general treatment of the subject of geochemistry is an extension and a bringing-up-to-date of a book previously published in Finnish by Sahama. It is about as up to date as a book of this size and scope can be made. Papers published up to the early part of 1948 are included in the Bibliography, and their results are incorporated in the text.

Geochemistry contains too much detailed information for effective use of the volume as a textbook of the subject, yet it makes no pretense of being a compendium of all geochemical information. It is intended primarily as a reference work for the use of "the geologist who has the necessary background in chemistry and of the chemist who possesses an adequate knowledge of the geological sciences."

In a Foreword entitled "What Is Geochemistry?" the authors discuss the definitions of geochemistry which have been used in the principal geochemical works that have thus far appeared. They find themselves more nearly in accord with Goldschmidt's definition than with any other and accordingly adopt his concept of the three tasks of geochemistry: (1) to establish the abundance relations of elements and nuclides in the earth; (2) to account for the distribution of elements in the geochemical spheres of the earth; and (3) to detect the laws governing the abundance relationships and the distribution of the elements.

Rankama and Sahama adopt the following four geochemical spheres—the lithosphere, the hydrosphere, the atmosphere, and the biosphere—treatments of which constitute the four branches of geochemistry, i.e., lithogeochemistry, hydrogeochemistry, atmogeochemistry, and biogeochemistry. The book is divided into two parts: (1) "General Geochemistry" (412 pp.) and (2) "Manner of Occurrence of the Elements" (376 pp.). The threefold task and fourfold division of the subject of geochemistry provide the skeleton around which part 1 is built. The first four chapters deal in considerable detail with the task of geochemistry: (1) "Composition and Structure of Meteorites," (2) "Abundance of Elements and Nuclides," (3) "Geochemical Structure of the Earth," (4) "Distribution of the Elements among the Geochemical Spheres of the Earth." The succeeding four chapters are discussions of the geochemistry of the four geochemical spheres in the order in which they are named above.

In these chapters on the geochemical spheres many data on composition are given, but the emphasis is always on averages and on why elements behave as they do in concentration and dispersal rather than on the primary data. This point of view sets this section of *Geochemistry* definitely apart from Clarke's *Data of Geochemistry*. The difference can be illustrated by some figures on the respective treatments of the hydrosphere. In *Geochemistry* the chapter on the hydrosphere occupies 37 pages and gives a total of 34 individual analyses of all types of naturally occurring waters. In the *Data of Geochemistry* four chapters totaling 155 pages are devoted to the hydrosphere and 562 individual water analyses are given.

Part 1 concludes with two general chapters: (9) "Cosmochemistry and Geochemistry" and (10) "Outline of the Geochemical Evolution of the Earth."

In part 2 thirty-six chapters are devoted to the manner of occurrence of the elements, one chapter being devoted to each element or related group of elements. For example, hydrogen, carbon, silicon, nitrogen, oxygen, uranium, and many other elements are treated individually, with an entire chapter devoted to each one, whereas the alkali metals, the rare-earth metals, the platinum metals, the halogens, the inert gases, and other groups of elements are treated in single chapters. Within each chapter the general treatment is the same: "Abundance and General Geochemical Character," "Occurrence in Igneous Rocks," "Cycle and Biogeochemistry." There is, of course, necessary deviation from this simple outline for many of the elements. For example, in the chapter on carbon there is a section on "Cycle of Carbon Dioxide" between the "Atmosphere and the Sea"; under

oxygen there is a discussion of "Oxygen Isotopes," and for many of the elements, especially the metals, there is a section on "Ores." This detailed and exhaustive treatment of the elements is in sharp contrast to that in the *Data of Geochemistry*, where the nature and relative abundance of the elements are summarized in 40 pages and where many of the elements are dismissed with a line or two and not as much as half a page is devoted to any one of them.

Following the 789 pages of text, there are seven well-chosen appendixes which are useful in a reference work of this kind: (1) "The Periodic System of the Elements," (2) "Atomic Weights for 1948," (3) "Atomic and Ionic Radii of the Elements," (4) "The Electronic Structure of the Elements," (5) "Geodetic and Other Terrestrial Data," (6) "Gravimetric Conversion Factors," and (7) "Various Ways of Expressing Concentration or Content, Commonly Used in Geochemical Calculations."

It is interesting to note that in the Bibliography of 735 titles, only about 6 per cent are of papers that appeared before 1920 and 9 per cent between 1920 and 1930. About 40 per cent appeared in the 1930's and 44 per cent in 1940 and subsequent years. This is no doubt due in part to the great increase in numbers of geochemical papers in recent years. It is probably also a reflection of the fact that most of the data of the earlier papers were included in the last edition of Clarke's *Data of Geochemistry* and that the concepts of many of the earlier papers are now completely outmoded.

There is an author index of 7 pages and a subject index of 64 pages, the latter containing some fourteen thousand entries. This is almost twice the number of entries in the Index of the last edition of the *Data of Geochemistry*, for almost exactly the same number of text pages. In spite of this great number of entries, their manner of selection and arrangement leaves much to be desired. For example, of 82 references to "Granite," only two give a subheading, the other 80 being strung out as a mere list of pages. If one is interested in some particular feature of granite, therefore, he may have to look up all 80 references to locate it or to satisfy himself that that particular feature is not treated in this book. This same unsatisfactory method is used for most of the entries for which there are many references, such as basic rocks, clay, diadochy, evaporates, feldspar, lithosphere, marine sediments, metamorphism, organisms, sun, transportation, and all similar entries. This same criticism applies to the author index in cases where there are many references to one author. For example, there are 119 page references to work by V. M. Goldschmidt, with no indication of the subject matter of a single one of them. For at least 28 other authors there are 10–51 references to each, treated in the same manner. Some indication of the topic of each of these references would have made the index much more usable. The chemical elements, on the other hand, are indexed adequately with suitable subheadings.

Many subjects treated in the text are either not listed in the index or occur only as subheadings where they are difficult to find. For example, there is no reference in the index to either "Inclusions, liquid," or "Liquid inclusions." If one is interested in this subject, he must dig the information from the text or hope to find all the references to liquid inclusions under such entries as "Granite, salt solutions in cavities of," and "Quartz, chemical composition of liquid inclusions in." One feels that liquid inclusions in sphalerite and galena must be mentioned in a work of this kind, yet there is no indication of such mention in the index. The references can be found only by looking up all the references to these minerals or, if one knows who did the original work, by looking up the references to the original author(s).

Temperature data in the text are scanty, but there is a number of references to temperatures of formation, alteration or reaction of minerals, to probable temperatures of formation of nuclides, etc.; yet one looks in vain for an entry in the index on "Temperature," "Thermometry," or the like; there is a single reference to "Geological thermometer," and that is to an incidental remark that the scandium content of biotite may sometimes be used in a general way as a geologic thermometer.

These shortcomings of the index considerably reduce the usefulness of the book as a reference work. Not only do they make much more laborious than it should be the task of getting information on a given subject, but they also leave one wondering, after he has exhausted the index references, whether the information he sought, or more information than he found, may not be hidden somewhere else in the text.

Rankama and Sahama have done a remarkable job of compiling facts and outlining theories in this broad and rapidly developing field. The book is well printed on good paper, and typographical errors are very few. The authors and the University of Chicago Press are to be

congratulated on producing one of the outstanding scientific books of the year. The price puts it out of reach of the average student, but it is a "must" book not only for geological and chemical libraries but also for more general technical libraries everywhere.

It would be impossible, however, for two individuals to cover so wide a field without some significant omissions and errors. *Geochemistry* is not entirely free of such omissions and errors, and therefore some specialists will no doubt be disappointed in the treatment of their particular spheres of interest. For example, it is astonishing to find no reference in the discussion of differentiation to the vast amount of pertinent experimental work or to the best and most detailed field investigation of this subject ever made. Bowen's reaction series is given at the beginning of the discussion, but no silicate phase equilibrium diagrams are given, nor is any mention made of this important phase of laboratory work which has added so much to our understanding of the processes of differentiation. The very detailed study of the petrology, chemical composition, and differentiation of the Skaergaard intrusion, by Wager and Deer, together with subsequent work on the minor elements in these same rocks, by Wager and Mitchell, would have made a wonderful example to illustrate the crystal-chemical approach which Rankama and Sahama employ throughout their book and particularly in the discussion of differentiation. Yet there is no reference to this work on the Skaergaard intrusion, nor are the papers listed in the Bibliography. On page 152 tridymite and cristobalite are said to be mineralogical curiosities; yet Larsen has estimated that in the San Juan Mountains alone there is present enough of these minerals to cover the state of Massachusetts to a depth of 10 feet. They are rare as compared to quartz, certainly, but do not belong with the very rare minerals classed as curiosities.

On this same page and again on page 555 the statement is made that quartz has no cleavage. It has at least one fairly well-developed cleavage parallel to the unit rhombohedron, as has been demonstrated repeatedly. This cleavage is referred to many times in the literature and is used consistently by quartz miners in trimming crystals.

The subject of dolomitization is not given treatment commensurate with the importance of this process in nature. A part of one paragraph is devoted to it under "Geochemistry of the Lithosphere" and slightly more than a page in the chapter on "Magnesium." In the former the statement is made that "all gradations probably exist between pure calcitic limestones and pure dolomites." Following as it does immediately after a discussion of the structure of calcite and dolomite, this statement is likely to be interpreted to mean that there is a complete series of solid solutions between the minerals calcite and dolomite, which is not the case. The work by Faust and Callaghan on dolomitization is not mentioned, nor is the earlier exhaustive study by Sander.

Geobotanical, geomicrobiological, and biogeochemical prospecting are mentioned very briefly, but nowhere is the broader and more important subject of geochemical prospecting discussed. This omission may be due in part to the fact that much of the literature of this subject has appeared in papers written in languages other than English, French, and German. The authors state in the Preface that they did not especially try to cover these papers because, in their opinion, "such papers generally are not addressed to the international reader." Surely, a new method of locating ore deposits is of more than national concern. The reviewer is of the opinion that papers in other languages on other fields of geochemistry might also have been included with advantage.

The chapter on uranium is not very satisfactory. This is partly due to neglect of earlier literature but more largely to the fact that a great deal of the work on uranium has not been published. The old value of 7.1×10^8 years is given as the half-life of U^{235}, whereas the best value now is 8.91×10^8 years, with an uncertainty of about 20 per cent. In addition to the radioactive isotopes with long half-life mentioned in the last paragraph of page 633, Re^{187} should be mentioned. The discussion of uranium minerals on page 635 is sketchy, and it would have been well to include a review of uranium-bearing minerals in which uranium occurs in important amounts, although it is not a major constituent and therefore does not appear in the formula.

The above-mentioned facts about uranium are in the literature. The ones that follow have, for the most part, not been published. They are mentioned here for the information of readers who are interested particularly in the geochemistry of uranium. The table on page 634 shows uranium contents of igneous rocks up to about 4 g/ton, but some alkalic rocks, such as phonolites, contain as much as 20 g/ton. On page 636

the statement appears that "enrichment of uranium is negligible in sediments devoid of organic matter." There are several types of sediments devoid of organic matter in which abnormal concentrations of uranium occur (for example, the Florida phosphates and the calcareous argillites of Great Slave Lake). Recent work by the U.S. Geological Survey has failed to demonstrate any correlation between potassium and uranium contents of organogenic black shales (p. 637). On the same page the statement is made that "petroleum and associated brines are always rich in uranium." These materials are usually high in radioactivity, to be sure, but it has recently been demonstrated that commonly, if not always, the abnormal radioactivity is due to radon rather than to uranium.

On page 638 the statement is made that "the most important feature of the biogeochemistry of uranium is its enrichment in sedimentary rocks as a result of biological processes." The best evidence now is that this concentration is not the result of biological processes at all, but of later chemical processes that are probably related, at least in part, to the presence of the organic material in the sediments.

As indicated above, these and other similar shortcomings may bother an occasional specialist, but they do not detract seriously from the most complete and up-to-date synthesis of the subject of geochemistry that has appeared in any language.

EARL INGERSON

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Probleme der Naturwissenschaften erläutert am Begriff der Mineralart. By PAUL NIGGLI. ("Sammlung Wissenschaft und Kultur," Vol. 5.) Basel: Verlag Birkhäuser, 1949. Pp. xi+240; figs. 100. Sw. fr. 18.50.

Professor Niggli's new book deals with problems of the natural sciences from the viewpoint of the concept of mineral species. It is a philosophical essay, discussing the broader values of crystallography and mineralogy, and is not addressed solely to professional mineralogists—in fact, it is written chiefly for biologists, chemists, and physicists concerned with the species concept.

Niggli emphasizes the value of philosophical synthesis and, in so doing, has recognized the importance of one of the most difficult problems which faces science at its present highly differentiated stage. He believes that the highest goal of the natural sciences is the achievement of knowledge through *Anschauung* ("intuition" or "perception," with a quality of directness and immediacy) and *Gestaltung* and regrets that problems of morphology and the concepts of "type" and "species," which are mainly philosophical questions, are not highly appreciated at the present time.

While stressing the morphological aspect of scientific problems, he also recognizes the importance of the dynamic viewpoint and believes that the two should be synthesized in order to formulate concepts definable in terms of morphological rules in conformity with dynamic laws.

The opening chapter deals with the scientific aspect of nature: the goals of the natural sciences, the presuppositions on which scientific understanding of nature is based, and the general methods of scientific research. In developing the latter topic, he differentiates two fundamental methods which he calls the "α-method" and the "β-method," on whose synthesis he believes that progress in science depends. The α-method consists of exact quantitative descriptions of idealized events which have been conceived from real events by generalization and abstraction; it aims at an explanation of causality by generally valid dynamic laws. In contrast, the β-method strives for a systematic description of structure and form; employing a knowledge of geometry and topology, it searches for homologies and analogies and creates group relations and correlations.

The second chapter is a philosophical discussion of the idea of individuality on which the species concept is based. Niggli points out that, since the shape of the individual is to some extent the result of interaction between the individual and its environment, the external form in itself is not evidence of pure individuality and must, in spite of its importance as a first approximation in conceptual formulation, be critically evaluated. The pure individual form can never be directly observed because environment is ever present, boundary conditions between the individual and its environment generally playing an increasing role with decreasing size of the individual.

Consideration of a section of nature as a whole is unavoidable when the parts of that whole are in intimate relation to one another. In a dynamic sense this leads to isolation and independence of the section. Furthermore, the combination creates something new. Here Niggli

appears to be influenced by Gestalt psychology. The concept *Gestalten* is based on the doctrine that in intellectual as well as in physical processes the whole displays properties other than those derived from the parts in mere summation. Niggli formulates three theses: (1) A real whole, which has natural individuality, is always something more than the sum of its parts, and hence is a new unit (*Einheit*). (2) A real whole permits no arbitrary dissection without losing its character. (3) If a whole is divided, the parts and the whole stand in an intimate, discoverable relation to one another; the parts are combined with one another (*Enkapsis*) and change their character forthwith when they are released from their association.

Thus, if a crystal is regarded as an individual, the question arises: Can the character of individuality be recognized also in crystal fragments? In a strict scientific sense the essential individual character of the whole must be distinguished from mere size and shape. Indeed, scientific crystallography was directed into proper channels by recognition of the fact that the essential character of the whole is not lost by division. The fact that fragments can be regenerated by growth to the original crystal form proves that fragmentation does not destroy the character of the individual. But there is a lower limit of division where the individuality-unit (*Enteloprot*) is reached. A single atom, for example, loses its individuality-character as soon as we consider it with reference to its constituents.

Chapter 3, on the crystal as a single individual (*phenotype*), discusses the characteristics of crystal form and the connection by morphological laws between crystal types different in metrical and symmetrical aspects. The author concludes that this connection resembles in many respects well-known morphological laws for forms of living organisms.

The following chapter uses rock salt in its octahedral and cubical forms to illustrate the type classification of crystal structures. He concludes that the great number of ideally imagined structural varieties in regard to symmetry, space requirements, and the formulation of conformable laws governing the atomic parts are deducible from a comparatively few fundamental construction principles.

Next he takes up the ideas of genotype and phenotype. In order to visualize crystal type, the observable properties of a crystal must be compared with and referred to structural characteristics. The question arises: What sort of correlation exists between the growing crystal and its structure? Experience has shown that the same crystal type can form crystals with different kinds of boundaries, so that, even in the case of the same internally operating disposition factors (*Anlagefaktoren*), the face development can be changed in the course of growth by changing the environment. Consequently, external form cannot be correlated with internal structure alone. Niggli concludes that, because of interaction with the environment and the complexity of the processes of growth, the external form of the crystal is always only a coarse structural image which never gives clear evidence of the details of the structure.

In chapter 6, "The Ideal and the Real Crystal," he points out that two individuals are never alike in every respect. In contrast to ideal crystals, real crystals are, so to speak, pathologically altered individuals. The science of crystal pathology, which is receiving increasing attention with the expanding technical uses of crystals, aims to establish the cause of the peculiarities, to specify the nature of the irregularities, and to find preventive methods and remedies for the pathological conditions.

Next, Niggli discusses the necessity of the species concept. Although different opinions exist concerning the distinction between species and about the philosophical importance of the concept, scientific research would hardly be possible without some agreement on these matters. The species concept must be understood in such a way that it is provisionally possible to classify individuals which are widely separated in time and space. In morphological differentiation of types, consideration must be given to natural boundary lines, as well as to those parts which remain together as a genetic unit (*Einheit*). Therefore, all crystals of the same structural type cannot be united in one and the same species. The following is offered as preliminary guidance: ***A group of crystals belong to the same crystal species when, within the limits of experimental error, they exhibit an observable continuity of properties or form a connected series.*** Thus, if experimental investigation shows that two naturally occurring minerals are related and linked together only by a continuous series of connecting artificial minerals, this is sufficient reason for classifying them together. That minerals formed under two different sets of conditions are members of the same species must be proved.

The variability of crystal species from the

ideal picture of their inner construction is next discussed. The properties of a mineral are determined only in a preliminary way by knowledge of the species or species group to which it belongs. The chemical composition may vary considerably because of simple or complex atomic substitution or the presence or absence of inclusions. A mineral species is not characterized by an inflexible and unchangeable fundamental construction principle but can adapt itself to some extent to environment and has a fundamental persistence ability which protects it against environmental conditions endangering its existence. The environment modifies it, but the fundamental construction persists within a certain range.

Chapter 9 continues the discussion of the variability of the ideal crystal species as a consequence of environmental physical conditions. The author claims that crystals are truly representative of the inorganic world in their well-defined and, in several respects, related species, some of which show great variability and adaptability. The connections which appear in morphological classifications of types correspond, at least in part, to actual intimate relationships. The classification of species is partly a purely morphological science, but, for transitional and metamorphosed minerals, verification must be made by physical-chemical means. The science of mineral species arises from combinations of, and intimate interaction between, his α- and β-methods.

The inner variability of crystal species in respect to their real construction is next discussed. A crystal reacts to certain kinds of environmental disturbances by "trying" to restrain the effects of the latter and to develop a transitional structure adapted to the conditions.

Next, the science of mineral associations is taken up. The author feels that the concept of natural associations, although still difficult to define clearly, is beginning to have a definite place in scientific terminology. Ordinarily, this concept is employed only when the constituents of a macroheterogeneous formation stand in a characteristic correlative relation to one another and tend to achieve a sort of equilibrium without substantial loss of their individual characters. The term "aggregate," on the other hand, implies no such association. Between these two extremes are individual units combined in accordance with certain laws; the concept *Ganzheit* is applicable to such combinations.

Goethe long ago observed that quartz, feldspar, and mica did not exist as parts prior to their aggregation but originated with the granite of which they are constituents. The concepts *Gestein* ("rock") and *Gesteinsart* ("rock species") originated with observations of mineral combinations of limited variability in spatial units of some magnitude. Differentiation into rock types was achieved not only by analysis of separate mineral aggregates which showed repetition of a given combination of constituents; the properties of the whole (of the resulting rock) were studied not merely for the sake of the analysis as such but for knowledge of the essential properties of the whole (of the rock which these mineral assemblages made up).

In the final chapter Niggli points out that the object of its research determines the character of a science. The so-called "exact" sciences establish, first of all, the laws which are valid only under definite and relatively simple conditions. The more complex the object of research, the more difficult is the interpretation of the effects of the interacting forces. The natural scientist in his dealing with complex phenomena is confronting a difficult task, in that he has to consider not only the elementary and individual processes but also the structure and morphology resulting from the interplay of these processes.

This book is written for those who can appreciate philosophical methods and thinking. Except for formal details in support of the theme, the subject matter of the book is largely in a creative stage. The volume differs from detailed treatises by presenting the subject matter in a summary manner and requires as little knowledge of crystallographic details as is consistent with sound method.

Niggli's book is recommended to anyone on the lookout for new aspects of geology. The author's maxim, "In der Synthese liegt der Fortschritt," is advice which applies especially well to geological science in its present stage of evolution. Since the necessity for synthesis is usually created by excessive differentiation, the author could well have devoted a special chapter to problems of differentiation.

His discussion of several fundamental philosophical questions of scientific importance is enhanced by quotations from many eminent philosophers and scientists. It is unfortunate that the author has failed to provide many of his quotations with adequate references. A selected bibliography would have added to the value of the book, especially for the benefit of those philosophically unenlightened specialists

who, inspired by the author's stimulating thought, may wish to follow them up in one direction or another.

H. A. WADELL

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Hydrology. By C. O. WISLER and E. F. BRATER. New York: John Wiley & Sons, Inc., 1949. Pp. xi+419; figs. 132; tables 29. $6.00.

This book is a successful attempt to present the young science of hydrology in a clear, concise, and logical manner. The book contains a minimum of technical terminology and has the readability of a semipopular scientific article. It begins with a discussion of the hydrologic cycle, next the hydrograph and the drainage basin are discussed, and then the book treats each element of the hydrologic cycle, such as precipitation, water losses, infiltration, ground water, and runoff. These processes are treated in detail, yet the reading never becomes "heavy." Special chapters are devoted to the interesting subject of floods and to the important subject of streamflow records.

The outstanding feature of the book is the manner in which the authors have been able to integrate items collected from various books and papers (a surprising number from the *Proceedings of the American Geophysical Union*) into a comprehensive, yet simple, textbook of hydrology. Examples with illustrative figures, showing how various types of problems in hydrology are solved, are presented as an integrated part of the text. The book contains no sets of problems for student solution.

The book will serve as a nucleus about which the young science of hydrology can expand logically. The chapter on ground water by John G. Ferris can perform a similar function, in that it brings together into a chapter of 70 pages most of the recent advances in the study of groundwater hydraulics. For civil and agricultural engineers, ground-water geologists, and others interested in the occurrence and use of water on and within the earth's crust, the book will prove valuable. Where more detail or a fuller treatment of any particular subject is required, adequate references are furnished by the authors.

C. RICHARD MURRAY

Stanford University

Minerals of California. By JOSEPH MURDOCH and R. W. WEBB. (*California Div. Mines Bull. 113*.) San Francisco: State of California, Dept. of Natural Resources, 1948. Pp. 402; fig. 1; pls. 4. $3.00.

This volume is a revision of the *California Division of Mines Bull. 113* (1938), which itself was the fifth such catalogue of minerals found within the state, the first having been compiled in 1866 by W. P. Blake. The present list, complete to the close of 1945, includes 516 definite minerals plus many subspecies and varieties, an increase of 70 over the 1938 catalogue. The compilation has been completely rewritten; the authors have attempted to provide written confirmation of all occurrences. In its preparation they scanned all literature dealing in any way with California minerals; from this they have chosen some two thousand titles for the Bibliography, the largest published on California mineral occurrences.

The book begins with a page and a half of terse definition of such terms as "mineral," "igneous rocks," "amorphous," "gabbro," "limestone," "pegmatite," and "pseudomorph." Then follow fifteen pages of "Historical and Geological Sketches," chiefly quotations from original sources on such topics as "Borax," "The Discovery of Gold in California," and "The Crestmore Pegmatite Gem Area of Southern California." After a listing, according to the Dana classification, of all the California minerals so far discovered, the heart of the book begins. The minerals are discussed in alphabetical order, with their chemical composition, crystal system, structure, cleavage, luster, color, streak, hardness, specific gravity, chemical identification tests, and usual mode of occurrence, followed by a listing of all known California occurrences, usually in such detail that they could be found by anyone wishing to collect specimens or study the deposits *in situ*. These localities are keyed to the Bibliography. There are four color plates, showing five minerals and two types of gold.

The book should be useful to geologists wishing to collect or study the rarer minerals, particularly the thirty-nine which have not been found outside California; to Californians who would like to collect local minerals or those available by short trips (although they would have to look all through the book for this, as there are no county listings of minerals). It

would also be useful in giving clues to prospectors in search of mineral deposits. It would not be too helpful to anyone trying to identify a mineral that he had found, for the book does not include identification tables or even a listing of minerals likely to be found in a certain locality (except for the important localities, which are taken up specifically in the early portion of the book). It would be of little value to the layman seeking to understand the chemistry or genesis of mineral deposits or even the fundamentals of mineralogy. But these are not the purposes of the book, and there are many elementary mineralogy texts on the market which could serve this aim for the amateur or beginning mineralogist.

LOU W. PAGE

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Tectonique antéstéphanienne du Massif Central. By ANDRÉ DEMAY. ("Mémoires pour servir à l'explication de la Carte Géologique Détaillée de France.") Paris: Imprimerie Nationale, 1948. Pp. x+259; figs. 48; pls. 9.

The French Massif Central, or Central Plateau, occupies an important position in the structure of western Europe, as it has been regarded as something like a node in which the northwest-striking Armorican and the northeast-striking Variscian branch of the late Paleozoic European mountain systems join. An approximately rectangular area, 240 by 180 miles, is underlain by metamorphosed rocks and folded early Paleozoic formations. Here and there, latest Pennsylvanian sediments (the Stephanian of the French geologists) transgress discordantly over them, and the great masses of Tertiary lavas and extinct volcanic centers surmount them near the core of the plateau. Dr. Demay's memoir is concerned with the structure of the pre-Stephanian rocks only.

In several marginal belts of folded rocks, scattered finds of fossils, ranging from Lower Cambrian through Devonian in age, have permitted some measure of classification and age assignment for the various deformed, metamorphosed, or intrusive rocks of the region. Gneisses and schists of probable pre-Cambrian age are known from the extreme northern and southern borders of the massif, whereas, according to Demay, nearly all the rocks of the central area acquired their present structure during the Carboniferous, although it stands to reason that the sedimentary members of numerous metamorphosed zones must be pre-Carboniferous in age.

The geology of this large and geologically complex region has been investigated by J. Bergeron, F. Blondel, M. Boule, J. Durand, P. Glangeaud, L. de Launay, Al. Michel-Lévy, G. Mouret, E. Raguin, P. Termier, M. Thoral, and others. Dr. Demay began his studies about 1924 and is well qualified to attempt a synthesis of the structure and relationships of the rocks. Although it is impossible for an outsider to follow all the detail of description and localities, without recourse to the numerous sheets of the "Carte Géologique de France," some of the salient points of Demay's interpretation may be briefly sketched.

The crystalline rocks may be grouped into a number of arcs, convex to the south, traversing the Central Plateau from east to west. The curvature of the arcs is the important structural element that links the Armorican and Variscian mountain ranges. From north to south, Demay distinguishes the following arcuate zones: Lyon, northern Cévennes, central Cévennes, including the dome of Rouergue, southern Cévennes and, far to the south, the Montagne Noire. The continuity of the arcs is somewhat marred and disturbed by north-south sags or faults, such as the famous "coal channel" and the fault of Argentat that has been traced over more than 150 miles.

The zone of Lyon displays a series of gneisses that dip northwest and rest on mica schists. As this series is followed down in the section, the metamorphic rank of the formations decreases until nearly unmetamorphosed members are encountered. Demay assumes, therefore, that the sequence is inverted, and he interprets the zone of Lyon as a root zone in the sense of the Alpine geologists. Great thrust sheets of metamorphic rocks are believed to have protruded from here to the southeast, south, and southwest, resting now on lower metamorphic rocks. These sheets have been mapped, and their complicated shapes are shown in several cross sections. Erosion has removed many portions of the sheets, and intrusions have disturbed the connections in many areas. A small remnant of a sheet, near the root zone and close to the eastern border of the region, is the nappe of Gier. Farther south and west is the nappe of La Margéride, believed to have traveled 31 miles (50 km.). The age of the rocks within this sheet is uncertain; Demay favors the Carboniferous. South of these thrust sheets rises the remarkable dome of Rouergue, with a core of migmatites and with gneisses and

schists of lower metamorphic rank on its flanks. According to Demay, this is not an autochthonous massif but another thrust sheet that has subsequently been domed.

South of this dome are belts of isoclinally folded low-rank metamorphics, overturned to the south and southeast, the "isoclinal complex of the Orthocévennes," and the mountains of Lacaune, where Cambrian and Ordovician fossils have been discovered amid the folded strata. Northeast of the Lacaune Mountains are the Paleozoic rocks of the vicinity of Le Vigan, also considered to be parts of a thrust sheet which moved to the south. The southward-overturned folds of the Lacaune Mountains rest on an old east-west-trending block—the Montagne Noire, whose northern half is believed to contain true pre-Cambrian rocks, whereas its southern slopes display younger formations, folded and overturned to the north. This ancient block of the Montagne Noire has something like a counterpart along the northern border of the Central Massif, where also an east-west-trending belt—the Morvan-Roanne zone—comprises a pre-Devonian basement, including injection gneisses, perhaps of pre-Cambrian age. Upper Mississippian (Viséan) and, in places, Devonian rocks transgress it.

The reconstruction of the movements which produced this complicated structure of the Central Massif is rendered extremely difficult because numerous granite and monzonite massifs appear to have been emplaced after the thrusting. Thus the root zone of Lyon is believed now to be the roof of a batholith (pls. 3 and 4) some offshoots of which already penetrate the crystalline rocks at the surface. Elsewhere, Demay distinguishes syntectonic granites, sheetlike and with dominantly concordant contacts, from posttectonic massifs that cut across their wall rocks discordantly. The large granitic massif of Guéret in the northwestern portion of the Central Plateau, the equally large Forez granite in the northeast, and smaller masses in the northern Cévennes are thought to be syntectonic, but the granite of La Margéride, near the center of the region, as well as the smaller, outlying massifs of Saint-Guiral, Aigoual, and Mont Lozère, are posttectonic. All, however, are interpreted to be of Carboniferous age.

Because the intrusions have modified greatly the outcrop patterns, as well as the metamorphic characters and structure of the deformed crystalline rocks, the evidence upon which the picture of far-traveled thrust sheets rests is not everywhere so clear as might be wished Gneisses resting on less-metamorphosed crystalline schists is probably a trustworthy criterion for inverted sequence. Fortunately, the soles of several of the thrust sheets exhibit magnificent mylonite zones. Elsewhere, it has apparently been necessary to rely on similar lithologic sequence, when faulted, or isolated, sequences of metamorphosed rocks had to be correlated across granitic terranes. Where the sequences are not identical, the position of one or more particularly significant members seems to have guided the interpretation. Even though the exact number of miles that individual thrust sheets have moved may be in doubt, the prevailing low dips, the position of gneisses on schists and phyllites, and the distribution of mylonites are in favor of appreciable subhorizontal movements.

It is much to be regretted that there is no reference in this memoir to lineation in the metamorphic rocks. For the reconstruction of the directions of principal yielding in the crystalline rocks, the systematic measuring and plotting of lineation and axes of folds would undoubtedly have contributed some of the most reliable supporting evidence. Perhaps this has been done in the many geological quadrangles and accompanying bulletins of the detailed geologic map of France; but the reviewer has not seen them. Although the last word on the structure of the Central Massif has probably not yet been said, this memoir gives a welcome review of the present status of geologic research in this interesting and problematic region.

ROBERT BALK

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Microtectonique et tectonique profonde—cristallisations et injections magmatiques syntectoniques. By ANDRÉ DEMAY. ("Mémoires pour servir à l'explication de la Carte Géologique Détaillée de France.") Paris: Imprimerie Nationale, 1942. Pp. xx+260; figs. 29; pls. 19.

The author defines his terms as follows: "microtectonics" is the study of microscopic structures caused by orogenic movements; "tectonics of the depth" (*tectonique profonde*) is the deformation of the earth's crust at those levels where the rocks have been metamorphosed, injected, and absorbed by magma that was active during the same orogenetic period (p. xii). The volume

contains extensive descriptions, accompanied by briefer discussion, of microscopic features, such as replacement phenomena; growth and deformation of crystalloblasts; evidence of pre-, para-, and postcrystalline deformation in rock fabrics; shear zones; mylonites; stages of recrystallization in rocks, more than one generation of one mineral in thin sections showing varying degrees of strain; trains of oriented inclusions in porphyroblasts; small-scale zigzag folds; etc.

All examples are taken from the crystalline rocks of the Central Massif of France, which the author has studied for several decades. Photographs of hand specimens and sketches further supplement the descriptions. The photomicrographs, in eighteen plates, are exceedingly well reproduced, and the detailed captions give complete descriptions of each picture.

The accompanying text is a detailed discussion of criteria found useful in interpreting the history of highly deformed, metamorphosed, feldspathized, injected, or recrystallized rocks, with special reference to the great thrust sheets, mylonite zones, and concordant gneiss sheets of the northern Cévennes, outlined briefly in the preceding review. If the reviewer understands the author correctly, Demay assumes (pp. 170–172) that, in this eastern portion of the Central Massif, thick sheets of gneiss and schists slid over a substratum of gneissic monzonite, the Forez granite, but that the latter was sufficiently hot to produce considerable recrystallization in its roof after the movement had died down. The gneissic monzonite itself, however, is believed to have moved subhorizontally to the south (p. 171). According to the author's 1948 memoir, the Forez monzonite would be one of the syntectonic intrusives of the Cévennes, probably of Mississippian age.

The descriptions and illustrations of the volume are useful, as they demonstrate many typical petrographic features of gneisses and also, as the author emphasizes, in that they show the close resemblance in geometric form between large-scale and small-scale deformation patterns.

ROBERT BALK

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Minerals and the Microscope. By H. G. SMITH. London: Murby & Co., 4th ed., 1940; 2d reprinting, 1949. Pp. xiii+130; 16mo; figs. 33; pls. 13. $1.10.

This booklet was first published in 1914. It may be employed as a text in the briefest possible course in the study of rocks where thin sections and the polarizing microscope are used. The first sixty-two pages deal with optical crystallography; there is a color print of Newton's scale and a plate of six photographs of interference figures. The next twenty-three pages give brief descriptions of the common rock-forming minerals as seen in thin section; eleven plates of four to six excellent photomicrographs each serve to illustrate this section admirably. Finally, forty-three pages are devoted to the study of igneous, sedimentary, and metamorphic rocks. These is a two-page Index. The major change since the third edition (1933) is in the discussions of igneous and metamorphic rocks.

D. JEROME FISHER

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Climate through the Ages: A Study of the Climatic Factors and Their Variations. By C. E. P. BROOKS. 2d ed. New York and Toronto: McGraw-Hill Book Co., Inc., 1949. Printed by Headley Bros., London and Ashford, Kent. Pp. 395; figs. 39. $4.50.

The appearance of an extensively revised second edition of this book is significant because it is essentially the only work in its field. Also it is a book that could have been written only by such a rare individual as Dr. Brooks, who has a background of training in both geology and meteorology.

Although twenty-two years have passed since the publication of the first edition, there is no change in the over-all organization and surprisingly few changes in the general conclusions. Half of the book is given over to climatic factors and their variations (pt. 1) and the remainder to geological climates and climates of the historical past (parts 2 and 3). As outlined by the author, the results of the study point to four main conclusions:

1. The major oscillations of climate, extending over millions of years, are due to orogenic cycles and resulting geographic changes. These may include variations in carbon dioxide and volcanic dust in the atmosphere.

2. Climatic oscillations lasting thousands or tens of thousands of years are due to (*a*) changes in land and sea caused by isostatic effects of loading by gradation and the growth of ice

sheets; (*b*) astronomical changes; or (*c*) possibly variations of solar activity.

3. Climatic oscillations of a few hundred years appear to be due mainly to solar variations.

4. Climatic variations of shorter periods may be due in part to solar variations, but they often appear to be caused by changes in the circulation of the atmosphere which may have no external cause. "They result from the interaction of the winds, ocean currents and floating icefields, which we know to occur, but which, in the present stage of knowledge, is incalculable."

In a final statement the author concludes that climatic changes can be accounted for by known causes and that it is not necessary to introduce hypothetical clouds of cosmic dust, strange stars, or great disturbances of the earth's axis of rotation.

In spite of a close similarity in organization and general conclusions, much of the book has been rewritten, and well over one-third of the references are new. The discussions of Pleistocene climates and climates of the historical past in Europe are based largely on recent sources.

Most of the geological objections to the author's conclusions probably will arise from the handling of paleogeographic interpretations, which are extremely tenuous at best and involve countless stratigraphic uncertainties. This is particularly true of the Upper Carboniferous, where the meteorological reconstruction is based largely on paleogeographic maps by Th. Arldt (1919). Here a more conservative interpretation, omitting an extensive Gondwanaland, could lead to far different conclusions. Another major uncertainty is involved in the correlation of climatic and orogenic cycles. Many geologists are not convinced of the reality of orogenic cycles, and, at most, the evidence is incomplete. Uncertainties also are involved in the acceptance of other geological interpretations, i.e., the warm periods of the geological past were also characterized by dryness; significant relief was caused directly by mountain folding; and intercontinental correlation of the closing stages of the Pleistocene is established by glacial varves. Geologists also may have some reservations about the great preponderance of warm, equable climates in the geological past because of the lack of climatic evidence for the long intervals of geological time represented by unconformities.

In connection with recent controversial issues, it is of interest that the Wegener hypothesis is again generally discounted; that the author goes far toward accepting the Spitaler-Milankovitch astronomic hypothesis for climatic stages in the Pleistocene; and that the glacial anticyclone hypothesis, although uncertain for the Greenland icecap, is retained for present Antarctica and the Pleistocene ice sheets.

The issues raised by the book are of major significance, and its vast scope provides a stimulating experience that should be enjoyable to all students of earth history.

LELAND HORBERG

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Geology of the Northwest Flank of the Gros Ventre Mountains, Wyoming. By FRANK ALBERT SWENSON. ("Augustana Library Publications," no. 21 [Augustana College, Rock Island, Ill.].) Davenport, Iowa: Commercial Printing Co., 1949. Pp. 75; figs. 14; pls. 2; frontispiece.

It is a pleasure to note the continued publication of geological reports in the Augustana series, which includes earlier well-known papers by Udden, Lugn, Fryxell, and others. This is the ninth geological paper in the series. It includes a straightforward description of the stratigraphy, structure, and geomorphic features of an area bordering the east side of Jackson Hole, Wyoming. The upper and lower Gros Ventre slides, described previously by other writers, are situated within the area. Laramide structures within the area are those of the structural foreland along the northeast border of the Rocky Mountain geosyncline. The structures are believed to continue northwestward into the Teton fault block, although interrupted by Tertiary faults along Jackson Hole. Glacial deposits correlative with Blackwelder's Buffalo, Bull Lake, and Pinedale stages are recognized within the area, and there is evidence that the Bull Lake may be represented by two substages.

LELAND HORBERG

University of Chicago

Die Randschwellen der Kontinente ("The Marginal Ridges of the Continents"). By OTTO JESSEN. Gotha, Germany: Justus Perthes, 1948. (*Petermanns Geog. Mitteilungen*, Ergänzungsheft 241.) Pp. 205; pls. 32.

The manifold problems of the belts of crustal elevation and disturbance along the

margins of the continents are discussed in this book by a competent geographer. In the first 127 pages the immense volume of descriptive material, covering systematically every continent, is portrayed in condensed but adequate fashion. Lists of references are given at the end of the discussion of each continent. For understandable reasons, the author has not had access to much of the modern non-European literature, but a synopsis of so large a complex of data makes interesting reading even where some of the latest views are not included. Simplified sections across typical continental margins and colored outline maps of the corresponding regions accompany the descriptions. It is surprising to see how many more of these disturbed marginal belts fringe the continents than one remembers from a physical map of the world, which does not bring out those that are deeply eroded. The author presents a large world map (pl. 32), on which the continents appear, for the most part, as a mosaic of basins, separated from one another and commonly from the oceans by structural ridges. He believes the data suggest a similar structural pattern on the bottoms of the Indian, Atlantic, and southeastern Pacific oceans.

In the second part (pp. 128–197) Jessen summarizes and discusses his findings. Commonly, high marginal ridges are associated with particularly deep, contiguous submarine troughs; conversely, where marginal ridges are lacking, the continental shelves are especially shallow and wide. Several geometric peculiarities are noted: curved marginal ridges are convex toward the ocean; where two coast lines converge, as in Mexico, the convex side faces the larger and deeper ocean. The majority of the ridges are asymmetric in cross section, the steeper slope facing the ocean. Toward the continent, the slope may be one gentle surface, or it may proceed in steps. The ridge may be a huge mountain mass, like the cordillera, or a zone of ancient, disturbed rocks, but topographically low, as they are found near the mouth of the Amazon. This mosaic of crustal blocks, revealed by the marginal ridges, is compared by the author with features of the moon, and he points out a number of perhaps significant similarities.

Where the geological record is complete, it can be shown that elevation of a marginal ridge coincides with depression of the adjacent sea floor, and the same principle is illustrated by measurements of differential elevation and subsidence caused by many recent earthquakes in such zones. Discussing the meaning of this interdependence, the author reviews gravitational data and is in substantial agreement with Vening-Meinesz' theory of the evolution of belts of negative gravity anomalies. "Cooling and shrinkage of the earth, periodically intensified, and regionally differentiated, produce tangential and radial stresses" (p. 144). These, he believes, are responsible in the last analysis for the pattern of disturbance. He elaborates the assumed mechanism in some detail and considers it possible that the lunar surface features may have developed in a somewhat similar manner. In the last three chapters the author discusses special structural and geomorphological features of the ridges, as well as their effect on climate.

Regardless of whether one agrees with the author in his major theories, the book is a comprehensive digest of the many facts about the earth's disturbed belts, and the numerous references, as well as the excellently printed plates, add to the value of this interesting treatise.

ROBERT BALK

University of Chicago

The Ocean. By F. D. OMMANNEY. London: Oxford University Press, 1949. Pp. 238; figs. 12; pls. 4.

The Ocean, a pocket edition (not to be confused with the much more weighty and authoritative *The Oceans*, by Sverdrup, Johnson, and Fleming), is an interestingly written compilation of information on the various fields of oceanography, with special emphasis on biology. It should serve the purpose of giving readers a workable knowledge of marine biology, marine chemistry, and physical oceanography. There is considerable mention of the geology of the sea floor, but the book seems to be hopelessly out of date in this field, virtually no reference being made to any of the geological explorations of the American marine laboratories.

The fine print is an unfortunate feature of the book, as is also the sparsity of illustration. However, the few well-chosen diagrams illustrating the important types of animal and plant life in the ocean will prove helpful to the reader.

Some of the statements indicate that the author has made very little study of geology. The following statements illustrate this point. On page 30: "The very earliest fossils, those of the

oldest Cambrian deposits . . ." needs no comment. On page 142: "In the middle of the broken coral ring lies a lagoon fifty to seventy fathoms deep." Actually, almost all coral lagoons are less than 30 fathoms deep. On page 155: "Between the deep and broad canyons are innumerable smaller chisellings, like the parallel rain gullies that can be seen on any soft railway embankment. . . ." The perusal of both English and American literature relative to the so-called "gullies" off the east coast would have shown the writer that they are not based on any actual information. On page 160: "The pumice of which the [red] clay is composed. . . ." This suggested composition for red clay is completely at variance with the known facts. On page 162: "No bottom sampling instrument has ever yet penetrated to the rock base which, at some depth, must lie beneath them. This is the true floor of the ocean basin but we can only guess its character." This statement is somewhat surprising in view of the large amount of publicity given to recent work by Maurice Ewing and Hans Pettersson. Some of their cores penetrated to rock base, and their geophysical investigations have given an important amount of new data concerning the thickness of overlying sediment and the nature of the basement.

Despite these criticisms, the writer feels that the book should be particularly helpful to students taking courses in oceanography or in reviewing for examinations in this subject. Because of its small size, it would be a useful book to take on a trip where both weight and space were limited.

FRANCIS P. SHEPARD

Scripps Institution of Oceanography

Structural Petrology of Deformed Rocks. By H. W. FAIRBAIRN (with supplementary chapters on statistical analysis by FELIX CHAYES). Cambridge, Mass.: Addison-Wesley Press, Inc., 1949. Pp. ix+344; figs. 273; tables 21. $12.50.

Dr. Fairbairn's well-known and extremely useful textbook on structural petrology is again available in a new and enlarged edition. The 1942 edition, itself the successor to a mimeographed outline, has probably been the most valuable standby for all American students of petrofabric work to whom Sander's publications were unavailable or too difficult to read. The new edition retains the three principal divisions, "Petrofabrics and Experimental Facts"; "Interpretation and Application"; and "Methods and Analytical Procedures." However, the sequence of chapters within these divisions has been changed by the incorporation of new material and the rewriting and rearrangement of many topics.

Under "Orientation Patterns of Minerals," new data are given on antigorite, olivine, pyroxene, apatite, ice, zircon, and diopside, and the results of recent studies by Tuttle and others on deformation lamellae in quartz have been included. A new chapter on "Orientation of Composite Elements" summarizes orientation studies on oöids, pebbles of conglomerates, porphyroblasts, and pressure shadows; another chapter, "Orientation Related to *s*-Surfaces," combines Ingerson's study of rocks with many *s*-planes, Kvale's investigation of the Norwegian Bergsdalen quartzites, and others by Sander and collaborators on orientation patterns along fractures.

The material of part 2 has been largely rewritten and grouped into chapters with these headings: "Development of *s*-Surfaces"; "Rotation and Relative Movement"; "Recrystallization in Tectonites"; and "Tectonic Transport." The literature has been incorporated very completely, and the discussion of many controversial topics is factual and to the point.

The third part, on methods and analytical procedures, has been left pretty much as it was, but Dr. Chayes's two concluding chapters on statistical analysis are new. When a rock fabric does not show a strong concentration of orientation elements but "weak maxima," distributed in more than one direction, the investigator may be at a loss to judge how far this pattern differs from the predeformation pattern of mineral orientation. In that case he will have occasion to read Chayes's explanation of how the chi-square test is made and how the so-called coefficient of correlation of varying elements is determined. It is regretted that Dr. Chayes does not define "degrees of freedom" and "independent linear constraints" (p. 298) as used in statistics. For readers not familiar with the terminology of statistics, the meaning of these and several other terms is not so obvious that they could derive the greatest amount of benefit from the interesting and pertinent discussion. Perhaps this can be improved at some future time.

The new edition has been prepared with great care. The text is for the most part clear,

and there are few ambiguities where a beginner may have difficulties in understanding the meaning. The numerous illustrations are well reproduced and the captions adequate. The number of symbols has been kept commendably low. Perhaps in a subsequent edition a glossary or table with all the symbols and their definitions could be added. It might help to make this subject more intelligible for the beginner. The reviewer would also suggest that in later editions some diagrams be added that connect fabric diagrams as closely with megascopically visible structure elements in the ledges whence the specimens were obtained as they do now with theories of slip and experimental work on deformation of crystals.

A Bibliography of 285 titles at the end of the book is most welcome; important references through 1948 have been included. The omission of years of publication in a few is a very minor oversight.

As Fairbairn's book is the only one in the English language that covers so thoroughly a large and important field of work, the excessively high price of the book is most regrettable, for it will obviously restrict the distribution of the book more than any other factor.

ROBERT BALK

University of Chicago

Pre-Chattanooga Stratigraphy in Central Tennessee. By CHARLES W. WILSON, JR. (*Tennessee Div. Geology Bull.*, no. 56). Nashville: Dept. Cons., 1949. Pp. xviii+407; figs. 89; pls. 28.

This report on the pre-Chattanooga stratigraphy of the Sequatchie Valley, the central basin of Tennessee, and the Tennessee Valley is the product of years of study of the outcrops by the author and a careful review of all previous publications on the area. The progress of correlations is shown in two tables. The field work for the report was begun in 1937.

The book is amply and effectively illustrated with stratigraphic sections and isopach maps. Over three hundred sections are described in detail and shown graphically to explain either lateral facies changes or relation of one formation to another. The locations of plotted sections are shown on ten index maps. There are thirty-three isopach maps, showing either thickness of facies or formations. Schematic cross sections, showing the relation of various facies, are used further to accent these important lateral gradations. A structural map of central Tennessee, contoured on the base of the Chattanooga shale, and a sub-Chattanooga geological map accompany the bulletin. These maps, on 1/500,000 scale, are folded into a pocket. There are twenty-six plates of Ordovician and Silurian fossils. These are grouped at the back of the volume.

More than half the volume is devoted to the Ordovician, the exposures of which cover a large area in Tennessee, ranging from Stones River through Richmond in age. Lateral changes in lithology are recognized, and the upper and lower limits of formations are clearly defined. Only one new name has been introduced, namely, "Inman," for the central Tennessee equivalent of the Eden shale. The Inman was recognized in Tennessee. Because it is a correlative of the Eden shale, the necessity for a new name is not clear. The writer is to be commended for his use of hyphenated names, such as Bigby-Cannon, for contemporaneous but contrasting lithologies instead of applying new names. There are a few controversial points of correlation in this group which are not mentioned by Wilson. One example is the problem of whether or not the Sequatchie in the northern part of the central basin is all Richmond in age.

The Silurian, so well exposed in the Tennessee Valley and in the Wells Creek Basin, has been studied by many geologists, and the succession in these areas has been used to tie together sections in the entire central interior of the continent. Wilson's carefully described sections and the thoughtful correlations will therefore prove extremely useful. A number of problems of correlation in the Silurian have been solved, and others may yet be solved by the use of these detailed sections. Wilson has brought Savage's work on the Devonian of the western valley up to date. One of the most valuable contributions is the recognition of correlative faunas in the Lower Devonian and the elimination of several confusing names.

This monograph is done in such detail and with such precision that it is possible to use the descriptions and illustrations of the author to correlate sections into the adjoining states. For this reason, it will prove valuable to other workers in the Ordovician, Silurian, and Devonian.

LOUISE BARTON FREEMAN

Lexington, Kentucky

Petrology of the Nor.hampton Sand Ironstone Formation. By J. H. TAYLOR. ("Geological Survey of Great Britain Mem.") 1949. Pp. 111; figs. 10; pls. 7 (4 colored). 12*s.* 6*d.*

This publication by the Geological Survey of Great Britain is the first major contribution to the petrography of the British bedded iron ores since Hallimond's classic study was issued in 1925.

The Northampton sand ironstone is an unmetamorphosed and essentially flat-lying rock of Jurassic age. It has a maximum thickness of about 30 feet. Workable ore is confined to those parts of the rock that have been enriched by near-surface oxidation. As in the United States, the gradual depletion of high-grade iron ores is forcing attention to the problem of beneficiation and utilization of lower-grade material. To those concerned with the problem of beneficiation this study provides a wealth of information on the mineralogy and chemistry of the ironstone. To students of sedimentation it is an important contribution to the knowledge of a quantitatively scarce, but widespread and interesting, rock type.

The unaltered rocks are composed of four dominant constituents: chamosite (an iron-rich chlorite); siderite; limonite (used as a general name for red-brown or brown iron oxides); and kaolinite. Oölitic structures are a characteristic feature. The oöliths (oölith = oöid = ovulite) are composed most commonly of chamosite or limonite; the groundmass is generally chamosite or siderite. Kaolinite appears to have formed by penecontemporaneous leaching of chamosite. Pyrite, collophane, calcite, ankerite, and dolomite are less common primary constituents.

Taylor introduces a terminology for the oölites based on the nature of both the oölith and the matrix material. Thus a rock with limonite oöliths in a siderite matrix is called a "sideritic limonite oölite"; one with chamosite oöliths in a matrix of chamosite and siderite is called a "chamositic sideritic chamosite oölite." The nomenclature is admittedly awkward in some cases, but it does lend itself to precision and seems to merit general use by geologists dealing with oölitic rocks.

The composition of the chamositic constituent is considered at some length. Great difficulty was experienced in obtaining pure samples because of the intimate mixture with other minerals, notably kaolinite and goethite. The $SiO_2:RO:R_2O_3$ ratio obtained is definitely different from other published values. The specific gravity, never greater than 2.9, is remarkably low for chamosite of the stated composition and refractive index (about 1.645 average).

The importance in beneficiation research of mineralogical composition, as distinguished from chemical composition, is stressed. The chief obstacle to the utilization of the Northampton sand is the ubiquitous chamosite. A satisfactory method for recovery of iron from chamositic rock has yet to be devised.

The evidence for origin of all the major constituents—chamosite, limonite, siderite, and kaolinite—by direct precipitation or sea-bottom reactions is considered conclusive by Taylor. The rocks are shallow-water deposits, as indicated by channeling and local current bedding. Apparently, the oxidation-reduction potential varied widely from place to place in the basin. Taylor accepts one essential part of the concept developed by Cayeux for the Jurassic oölites of France—that is, that the place of origin of an oölith (*milieu générateur*) often is distinct from the place of ultimate incorporation (*centre d'accumulation*). It is clear that in many ways the resultant oölite may be more like a clastic rock than like a chemical precipitate: the components may be, and often are, chemically somewhat incompatible, and the structure is that of a solid rock.

The report is nicely illustrated by photomicrographs in color. Although they seem to lack the clarity of black-and-white photomicrographs of similar rocks in other reports (especially those of Cayeux), the color more than makes up for the loss. The general practice of the Survey in giving the specimen numbers of all rocks described or illustrated is a commendable one and might well be adopted by other organizations.

HAROLD L. JAMES
U.S. Geological Survey

Étude pétrographique des minérais de fer oolithiques du dogger des Alpes Suisses. By L. DEVERIN. ("Matériaux pour la Géologie de la Suisse," Sér. géotech., pt. 13, vol. 2.) Lausanne, 1945. Pp. 115; figs. 5; pls. 20.

The Middle Jurassic oölitic iron-ore beds of Switzerland are thin and economically unimportant, but, from the point of view of sedimentary petrology, the rocks present the same problems as do the more extensive and valuable iron-rich oölites of other countries. Oölitic

rocks from six districts are described, and, although each district has some distinctive features, the similarities are greater than the differences.

The typical oölite consists of chamosite oöliths (Deverin uses the term "ovulite") in a matrix of chamosite and carbonate, but many variations are found. In some rocks the oöliths are made up of alternating layers of chamosite and iron oxides or of oxides alone or partly of siderite; the matrix may be chamosite, dolomite, iron oxide, or a mixture.

Deverin, following Cayeux, concludes that the original material was a calcareous sand composed of fragmental remains of marine organisms, especially echinoderms. In the first stage of development of the oöliths, these carbonate grains are partly or wholly altered to chamosite by reaction with sea water. It is in this conclusion that Deverin differs most strongly from the views of German and British workers. The latter consider that there is no evidence to indicate an original carbonate; they hold that most of the chamosite (and possibly the iron oxides also) are a primary precipitate.

The petrography of the minerologic changes that have taken place is given in great detail. Most of it is descriptive; optical and chemical data are relatively scarce, although two new analyses of chamosite are presented. Some of the mineralogic changes described are the results of sea-bottom reactions; others are due to diagenesis in the more or less unconsolidated sediments; still others are due to later metamorphism. Chamosite is shown to be especially susceptible to alteration during diagenesis and metamorphism, and frequently it seems difficult to separate the results of these two processes. Deverin shows that in many of the oölites, as, for example, those of the Erzegg and Planplatte districts, diagenesis has caused breakdown of the original chamosite to iron oxides or carbonates with release of SiO_2; some of the rocks contain as much as 30 per cent opaline silica. In others the chamosite may be reconstituted, generally to a chlorite that is lower in iron. In the Glaris area, chamosite has been altered locally to stilpnomelane. In the Windgalle district the rocks were strongly deformed during the Alpine orogeny, and the grains of some oölites are greatly attenuated. Much of the chamosite has broken down to yield magnetite, with dolomite, opaline silica, and albite as by-products of the reaction.

Although in many ways this volume is a spirited defense of Cayeux's theories of origin of the iron-rich oölites, Deverin himself departs considerably from Cayeux's doctrine of an orderly series of replacements (calcite→siderite→chamosite→limonite→hematite→magnetite), particularly with respect to the siderite, which he finds to be a late-stage mineral. Actually, the differences between Deverin's conclusions and those reached by such British workers as Hallimond and Taylor are not so great as they appear at first glance. Each postulates deposition in a shallow, wave- and current-swept marine basin during an era when the iron content of the sea water was abnormally high; each emphasizes the complex preconsolidation history in which, by physical transport of the grains and by periodic changes in the nature of the sea water, the oölitic grains were exposed to a variety of conditions before being finally entrapped in the mud that now forms the matrix of the rock. Deverin's views also have much in common with those recently expressed by Alling on the origin of the Clinton hematite of this country. All these workers agree on one essential point: that most of the observed replacements and alterations took place prior to lithification of the rock.

The first two chapters of the book present valuable material of a general nature: a discussion of terminology; a comprehensive review of the problem of iron-rich oölites; and a clarification of Cayeux's theories (with vigorous castigation of those who have disagreed).

An especially complete and useful Bibliography is given. The report is illustrated by 20 plates of photomicrographs of good quality.

HAROLD L. JAMES
U.S. Geological Survey

Geology and Economics of New Mexico Iron-Ore Deposits. By V. C. KELLEY. ("Univ. of New Mexico Pub. in Geology," no. 2.) 1949. Pp. 246; figs. 46; pls 16. $3.00.

This report, the second in a new series of publications in geology by the University of New Mexico, is based on work sponsored by the U.S. Geological Survey, the Division of Research and Development of the University of New Mexico, and the U.S. Bureau of Mines. It is divided into two parts. Part 1 (71 pp.) presents such topics as history, economics, general geology, and classification of the ore deposits; part 2 (155 pp.) consists of descriptions of individual deposits under county headings.

As might be expected in an area of such size and geological diversity as New Mexico, many genetic types of iron ores are found. Of them, only the pyrometasomatic and supergene deposits have yielded commercial ore, although some deposits classed as "syngenetic sedimentary" conceivably have potential value. However, all known deposits of iron ore in the state are described for "reasons of scientific record" or for "saving future useless examinations."

The major part of the known reserves occurs in the zone of pyrometasomatic alteration that surrounds the Fierro-Hanover granodiorite stock in Grant County. This zone, which is well known for its zinc and copper deposits, consists of silicate alteration of a series of Paleozoic limestones and shales. Most of the iron ore, chiefly magnetite, occurs in the El Paso limestone of Lower Ordovician age. The ore bodies are irregular lenses, more or less parallel to the intrusive contacts. The larger ore bodies are on the order of several hundred feet long and 20–80 feet wide. "Most of the mine-run of ore ranges from 35 to 45 percent iron. It is relatively high in sulfur and copper." With an output of about 5,000,000 tons, the Fierro-Hanover district accounted for 80 per cent of the iron ore mined in New Mexico in the period 1889–1946. The reserves of ore for the district are estimated at 17,000,000 tons indicated and 33,000,000 tons inferred. This is about 70 per cent of the total New Mexico reserves of 35–55 per cent ore.

The supergene ores of Boston Hill, also in Grant County, have yielded about 1,200,000 tons of manganiferous ore, and the reserves are estimated at 10,000,000 tons. The ore is a mixture of hematite, limonite, and pyrolusite, which essentially forms a gossan over a zone of primary magnetite, hematite, and sulfide mineralization.

Kelley describes beds of oölitic hematite in the Bliss sandstone of Cambrian age. The thickness of these beds (up to 20 feet) and their iron content (15–40 per cent) are roughly comparable to the corresponding features of the Clinton beds of the Birmingham district of Alabama; but, whereas the Birmingham ores are calcareous, the Bliss oölite is highly siliceous (33 per cent SiO_2), owing to abundant clastic quartz.

As implied in the title of the book, emphasis is definitely on the economic aspects of the deposits. Except in so far as they affect valuation, the author deals only briefly with such topics as mineralogy and ore genesis. One of the chief assets of the volume is the abundance of carefully drawn and well-reproduced detail maps. For the mining geologist and engineer charged with appraisal, these maps will prove invaluable.

The iron-ore resources of New Mexico are small compared with the national total, but they could be of considerable local importance. This compendium doubtless will be of aid in the orderly and efficient development of these resources.

HAROLD L. JAMES

U.S. Geological Survey

Introduction to College Geology. By CHAUNCEY D. HOLMES. New York: Macmillan Co., 1949. Pp. xxi+429; figs. 312.

Introduction to College Geology is a clearly written and profusely illustrated text, probably intended for use in a survey course on introductory descriptive geology. Holmes's approach is slightly different, in that he rightly combines physical and historical geology and treats them as a unit instead of making the customary artificial separation. The text is not well balanced, however. Descriptive paleontology receives top billing, and other phases of geology are subordinated or ignored. A. C. Lawson, T. C. Chamberlin, and L. Agassiz are the only geologists given credit for anything but photographs or diagrams. If a Mesozoic bee (p. 204, not 203) is geologically important enough to mention, then certainly the process of metasomatism might have received a line or two. The usual mediocre reference lists of introductory texts are not included, and nothing is substituted for them. The three hundred and twelve photographs and drawings are, for the most part, well reproduced. However, at least fifteen full pages of valuable space have been wasted on photographs and diagrams which show nothing significant, and another thirty-one pages of full-page scenic photographs and generalized diagrams could easily be reduced one-half without impairing their value. The sixty-eight photographs and restoration drawings of fossils could be reduced in both number and size. Thus, if space were at a premium, the reviewer can easily visualize forty pages in which the neglected phases of geology might have been treated.

All introductory texts—and this one is no exception—seem to suffer in greater or less degree from an unfortunate resemblance to a

catalogue of index fossils—one reads description after description and little more. Geology is much more than this: it is a science based, as we all know, on observational facts, concepts, theories, hypotheses, assumptions, and interpretations. Description is only a part of this whole. If description is used to build a concept, case, or idea—things that are religiously avoided in introductory texts—then its use is necessary. When it is used only for bulk and reading material, it is out of place. The purpose of any introductory instruction, whether by lecture or by textbook, is to teach the student to analyze, to interpret, and to generalize by working with data, theories, and hypotheses. In short, he should learn how to think and should not be told the final conclusion without the slightest hint of the evidence, background, assumptions, and weaknesses upon which it is based. In many cases he is not even told whether the conclusion is fact, theory, hypothesis, or just a vague idea. All these ranks of ideas are lumped together with complete disregard for their critical differences. Why must a student wait until he is a graduate before he realizes that all geologic problems are not solved; that geologic research does not need to be the description of a new area, structure, or fossil; that actually he is surrounded on all sides by a multitude of problems? The impact of a theory, idea, or controversy is not fatal to a beginning student. On the contrary, he likes it, and, more important, he needs it. The crying need, therefore, is not for a new text with better descriptions, better illustrations, or better organization of material but rather for a text that treats the development of the concepts, theories, and hypotheses of geology with reference to the observational facts upon which they are based. In short, such a text should offer its case in all its strength and weakness by presenting the data and showing the logical development of interpretations from it. Such an "ideal" text would be difficult to write, but steps in this direction certainly can and should be taken.

GEORGE W. DEVORE

University of Chicago

Manual of Spectroscopy. By THEODORE A. CUTTING. Brooklyn: Chemical Publishing Co., Inc., 1949. Pp. vi+220; figs. 28. $6.50.

A "manual" of spectroscopy, indeed! One wonders whether there is any real need of a book of this caliber. The author's Preface states that the book "has been written to assist those who wish to analyze ores, minerals, alloys, and inorganic chemicals, or wish to teach others to do so." What the author and his publishers have failed to indicate is that this book is intended for the use of the amateur and the hobbyist who want to make visual qualitative analyses by means of simple homemade apparatus, such as slits made of safety-razor blades, etc., which may be set up according to the author's instructions. Very definitely, the book is not for the serious worker in the field of spectrochemical analysis. It can scarcely be recommended even for the amateur who knows how to use one of the well-known handbooks on spectrochemical analysis and a set of wavelength tables as a guide to reliable information.

To claim considerable accuracy for such "quantitative" analysis as is described in chapter iv is a highly regrettable practice. If the analytical chemist supplied the petrologist with a statement of the chemical composition of a rock, indicating that the content of silica is, say, in excess of 50 per cent, that of alumina between 10 and 20 per cent, and that of soda between 1 and 10 per cent, there probably would exist no quantitative petrology. However, the corresponding practice with spectrochemical analysis is still widespread today, being cultivated even by responsible scientists who may express trace-element content in minerals and rocks either by a rough range of values or by visually estimated intensity of the spectrum line on an arbitrary scale. Such information is often supplemented by reproducing spectra by the plateful, covering, perhaps, an area of more than a thousand Ångstrom units. Such evidence would have been valuable ninety years ago, but it is obsolete today and cannot be recommended, inasmuch as satisfactory quantitative methods of spectrochemical analysis are known.

The author has devoted a special chapter (chap. v) to the use of the spectroscope in mineralogy. In this part of the book he gives the following list of the "main mineral classes": oxides, alumina, iron oxides, silicates, hydrous silicates, calcareous minerals, dolomite, magnesian minerals, sodium minerals, potash minerals, titanium minerals, carbonates, nonmetallic minerals, rare earths, rocks, and trace elements. The reader will learn, among other things, that "the sesquioxide Fe_2O_3 (hematite), the ferrous oxide FeO, and the combination of the two Fe_3O_4 (magnetite) form the third larg-

est mineral mass in the lithosphere" (p. 92) and that "rutile, TiO_2, constitutes a bit more than 1 per cent of the earth's crust" (p. 94).

The publishers, according to a statement on the dust jacket, are confident that chapter vi, "Characteristic Lines of the Elements," is one of the most valuable features of the book. Here the author lists the elements in alphabetical order and gives wave lengths and intensities for their characteristic spectrum lines. "Other information, either interesting or useful, has also been given" (p. 97) in this chapter of seventy-seven pages. However, most of the information is totally irrelevant and nonessential in a book on spectroscopy and consists of such data as are to be found in a text on inorganic chemistry published twenty-five years ago and in old price lists of chemical supply houses. Data on the use of the elements in medicine are profusely given, and actually no less than three M.D.'s have supplied the author with information and criticism while he was preparing his book. With all due respect to the medical profession, the reviewer cannot help feeling that it would perhaps have been advisable to have replaced a part of this medical authority by asking an individual with a B.A. in geology to read the manuscript before it was sent to the printer. Spectroscopic and other data on elements whose spectra are excited only in the discharge tube are totally irrelevant in this book, just as are the X-ray wave lengths of the hypothetical elements illinium and masurium. In like manner the infrared and ultraviolet lines in the list of outstanding arc lines given on pages 174–185 are only ballast. The reviewer also regrets that he fails to grasp the importance of the wave-length table-chart on pages 186–212.

The number of inconsistencies and errors is impressive for such a small volume. The Ångstrom unit is spelled in four different ways: Ångström, Ångstrom, Angstrom, and angstrom. The names of scientists are often rudely in error: Meggars and Meggar are used for Meggers; Priestly for Priestley; Moslander for Mosander; Hacket for Hatchett; and Pierre Curie is rechristened Jacques Curie, to quote a few illustrative examples.

The book comes complete with a Bibliography of sixteen titles and an Index totaling almost four pages.

KALERVO RANKAMA

University of Chicago

"Report of the Committee on a Treatise on Marine Ecology and Paleoecology, 1948–1949." HARRY S. LADD, *Chairman*. Washington: Division of Geology and Geography, National Research Council, 1949. Pp. 121; figs. 8. $1.00. Mimeographed

This is the ninth annual report of a series devoted originally to research in marine ecology and paleoecology and more recently concerned with the preparation of a treatise on these two subjects. The forthcoming "Treatise" is to be published in two separate volumes. Volume 1, entitled "Marine Ecology," is under the direction of Gordon Gunter; volume 2 is devoted to paleoecology and will consist of "Selected Analyses from the Geologic Record," as well as papers on the ecology of invertebrates, vertebrates, and plants. Both volumes of the Treatise will include annotated bibliographies.

This year's report contains a suggested bathymetric classification of marine environments, summaries of research in progress throughout the United States and on certain Pacific islands, a thirteen-page Bibliography of recent publications on marine ecology and paleoecology, and several completed portions of volume 2 of the Treatise. One chapter ("Paleoecology of the Early Ordovician Sea in Central Texas," by Preston E. Cloud, Jr., and Virgil E. Barnes) of the section entitled "Selected Analyses from the Geologic Record" appeared in the Report for 1947–1948. Two additional units are presented in the current Report: "Paleoecology of the Cambrian in Montana and Wyoming," by Christiana Lochman, and "Paleoecology of the Jurassic Seas in the Western Interior," by Ralph W. Imlay. Other completed portions of the Treatise included in the Report are "Ecology of Nonalgal Marine Plants," by Roland W. Brown; "Paleoecology of the Agnatha," by George M. Robertson; and "Types of Occurrence and Position of Bryozoa in Late Paleozoic Sediments of the Midcontinent," by Maxim K. Elias.

As evidenced by the completed portions of the Treatise, workers in marine ecology and paleoecology will find these volumes an excellent source of information as well as a stimulus to further research.

ROBERT N. GINSBURG

University of Chicago

Applied Hydrology. By RAY K. LINSLEY, JR., MAX A. KOHLER, and JOSEPH L. H. PAULHUS. New York: McGraw-Hill Book Co., Inc., 1949. Pp. 689; figs. 329; tables 83. $8.50.

In the field of hydrology there has existed, for the last twenty years or more, an almost complete void of reference and textbooks dealing with fundamental principles and techniques. This new book fills this void in an admirable manner. The scope as stated by the authors takes in "(1) the measurement, recording, and publication of basic data; (2) the analysis of these data to develop and expand the fundamental theories; (3) the application of these theories and data to a multitude of practical problems." In covering items 1 and 2, the book achieves a neat balance between hypothesis, basic theory, and empirical knowledge and between methods of data collection, methods of analysis, and presentation of data either as examples or as extreme values. It appears that the third item and the title, *Applied Hydrology*, are somewhat overambitious, since there are many practical hydrologic problems in such fields as municipal water supply, irrigation, drainage, soil conservation, flood control, and hydroelectric power development which require reference far beyond the scope of this book. On the other hand, it is obvious that provision for all such problems would require a library rather than an individual volume.

It is especially encouraging to note that the authors, in developing the scope and arrangement of their book, have fully recognized that work in applied hydrology requires a working knowledge of the earth sciences, including meteorology, geology, soil physics, and biology, and of hydraulics, as well as the pure sciences of mathematics, physics, and chemistry. For example, the chapters on climate, temperature in the atmosphere, atmospheric humidity, and winds describe and summarize the mathematical relationships of those fundamentals of meteorologic science which are pertinent to the understanding of hydrologic phenomena. Again, in their presentation of evaporation and transpiration the authors have described the basic relationships with physics of the air and plant physiology and have listed outstanding references, which invite a more thorough exploration of these fields. Three chapters, dealing with the basin, surface retention and detention and overland flow, and soil physics, present in a unique and usable form certain basic and measurable relationships between geomorphology and the hydrologic characteristics of a river basin, the surface characteristics of vegetation and soil and the hydrograph of overland flow, and the physical properties and interrelations of the soil components in relation to soil water.

The chapter on sedimentation presents up-to-date methods and theories. The new theory of the impact of raindrops on the soil is discussed in detail, and only time will tell whether it has received more space than its importance warrants. The discussion of sediment transportation includes the very important concept of the distribution of the various-sized particles within the flowing stream. Included are many of the bed-load material formulas, but omitted is Dr. Hans A. Einstein's theory of bed-load transportation. This is regrettable, since Dr. Einstein has a fresh and different approach which does not employ the duBoy theory of traction force. Time will probably show that density currents have received too much attention under the subject of reservoir sedimentation.

The chapter on ground water presents, in a form that is readily understandable, the basic concepts of ground-water hydrology. The discussions, although necessarily brief, fully cover the fundamental phases of the subject. Unfortunately, certain important applied phases, such as quantitative methods of ground-water investigations, the economic yield of ground-water reservoirs, the ground-water inventory, or pumping tests, are too lightly discussed or are not mentioned.

The presentations of stream-flow measurement, hydrograph analysis, runoff relations and distribution, and stream-flow routing are up to date, comprehensive, and explicit. Although no phase of knowledge in the field of hydrology has advanced so rapidly during recent years as that dealing with separation of hydrograph components and reconstituting the hydrograph through application of the unit hydrograph principle, the authors have kept abreast of the subject. The treatment of snow-melt runoff and of snow, ice, and frost in general will be of especial significance to hydrologists in the northern and western states. All these chapters should become classics for instructional purposes.

The chapter on design criteria presents a well-selected group of hydrologic tools for design rather than standards and tests, as might be inferred from the title. The designer, or any

other worker in applied hydroglogy, will be greatly aided by the three appendixes on graphical correlation, sources of hydrologic and meteorologic data, and physical constants, conversion tables, and equivalents.

HERBERT A. RIESBOL

Hydrology Section, U.S. Bureau of Reclamation

Seismicity of the Earth and Associated Phenomena. By B. GUTENBERG and C. F. RICHTER. Princeton: Princeton University Press, 1949. Pp. vii+273; maps 34. $10.00.

This is a book which the working seismologist cannot afford to miss. It contains a mine of information. It summarizes and supplements the extensive series of papers previously published by the same authors. It is intended as an evaluation of the relative seismicity of various parts of the earth and as a description of the geography and geology of the zones and areas that show greater seismic activity.

The volume is subdivided rather unconventionally, not into chapters but into topics. The principal headings are these: "Materials Used," "Classification of Shocks," "Frequency and Energy of Earthquakes," "Structure of the Earth," "Maps and Regional Discussions." The last topic comprises most of the book.

In selecting and classifying their materials the authors had in mind three principal objectives: precision in the location of the shocks, relative accuracy in the determination of their focal depths, and applicability of the criteria for the estimation of Richter magnitudes. It is obvious to anyone familiar with the subject that these objectives could not have been attained before the advent of modern instrumental seismology. Therefore, the authors have limited themselves to those earthquakes that occurred during the period 1904–1946, inclusive. They recalculated the epicenters of all well-recorded shocks in Milne's catalogue, the *International Seismological Summary*, and station bulletins of recent years. Turner's focal depths were checked or corrected on the basis of modern tables of travel times. In the case of more recent earthquakes the phases distinctive of deep foci could be used. In all cases an effort was made to determine the Richter magnitude, M, which has been related by Gutenberg to the total energy, E, in ergs through the formula: $\log E = 12 + 1.8M$. The original definition of M by Richter depended on the maximum trace amplitude occurring in the record that would be made by a particular type of Wood-Anderson seismograph at a distance of exactly 100 km. from the epicenter of the given earthquakes. This arbitrary definition was gradually modified for depth of focus and extended, in a somewhat cautious way, so as to cover all possibilities. Therefore, admitting the validity of the methods by which the magnitudes were derived, the authors made a statistical study of all the energy liberated in the various classes of earthquakes and found that by far the greater part was set free by a very few major shocks.

The core of the volume and the major contribution of the authors is the geographical study. The principal regions or units discussed are, first, the rim of the Pacific Ocean with 80 per cent of the shallow earthquakes, 90 per cent of these of intermediate depth, and all of the very deep shocks; second, the Mediterranean and Trans-Asiatic zone; third, the Mid-Atlantic Ridge and other submarine ridges; fourth, internal and marginal fractures of continental masses, such as Africa; fifth, regions of feeble seismicity, as in Europe; and, last, the great stable masses, including the central Pacific Basin.

The space assigned to the textual part of the volume is comparatively limited. Hence it would be unreasonable to expect a critical discussion of the entire literature of the subject. But the reader is surprised at the omission of some monographs which are of greater importance than many of those which are included. As an example, one looks in vain for any reference to the work of Dahm and Hodgson on earth structure.

J. B. MACELWANE, S.J.

St. Louis University

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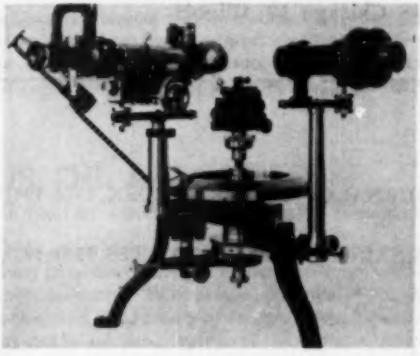

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